Search Results

[New Search]

Article Collection: View Collection Help (Click on the ☐ to add an article.)

You were searching for : ((plasma wavelength microwave distance)) usdate <=26-apr-2000
You found 28 out of 1045143 (28 returned)

Refine your query if desired:

AND ▼ [ ] in Abstract/Title/Keywords ▼ Refine

Last Page

Documents 1 - 25 listed on this page

	Score	Title	Author(s)	Citation
☐	77%	1.Extraction of radio frequency from electromagnetic surface waves guided by metallic strips PDF (50 kB) GZipped PS Order	M. Friedman	Rev. Sci. Instrum. **71**, 551 (2000)
☐	77%	2.Proper Motion of the Compact, Nonthermal Radio Source in the Galactic Center, Sagittarius A* Order	D. C. Backer and R. A. Sramek	Astrophys. J. **524**, 805 (1999)
☐	77%	3.Jet structure in the quasars 3C 345 and 1803 + 784 Order	L. I. Matveyenko and A. I. Witzel	Astron. Lett. **25**, 555 (1999)
☐	77%	4.Cathode multipactor induced by traveling waves PDF (4352 kB) GZipped PS Order	Spilios Riyopoulos	Phys. Plasmas **6**, 372 (1999)
☐	77%	5.Possibility of superluminal behaviors for X-like and Zenneck waves [PROLA Link] Order	A. Ranfagni and D. Mugnai	Phys. Rev. E **58**, 6742 (1998)
☐	77%	6.7 Millimeter VLBA Observations of Sagittarius A* Order	Geoffrey C. Bower and Donald C. Backer	Astrophys. J. Lett. **496**, L97 (1998)

☐	77%	7.The Gaussian Plasma Lens in Astrophysics: Refraction Order	Andrew W. Clegg, Alan L. Fey, and Joseph W. Lazio	Astrophys. J. **496**, 253 (1998)
☐	77%	8.Influence of the distance on the interaction between an autonomous pacemaker and a reentry [PROLA Link] Order	M. deCastro, M. Gómez-Gesteira, and V. Pérez-Villar	Phys. Rev. E **57**, 949 (1998)
☐	77%	9.Influence of the shape of small scatterers upon their resonance features [PROLA Link]	F. Bass and M. Fix	Phys. Rev. E **56**, 7235 (1997)
☐	77%	10.Super-Wide Electron Cyclotron Resonance Plasma Source Excited by an Independent Double-Slot Antenna Order	Hiroyuki Yoshiki, Shigeki Amadatsu, Koji Itadani, and Tatsuya Saijo	Jpn. J. Appl. Phys., Part 2 **36**, L1347 (1997)
☐	77%	11.The subarcsecond radio structure in NGC 1068. II. Implications for the central engine and unifying schemes Order	J. F. Gallimore, S. A. Baum, and C. P. O'Dea	Astrophys. J. **464**, 198 (1996)
☐	77%	12.1985 Voyager 2 radio ranging measurements of coronal density: Asymmetry in the radial profiles explained Order	Richard Woo	Astrophys. J. Lett. **458**, L87 (1996)
☐	77%	13.Self-consistent nonlinear theory of a premodulated electron beam propagating through a drift tube PDF (176 kB) GZipped PS Order	Han S. Uhm	Phys. Plasmas **3**, 168 (1996)
☐	77%	14.Characterization of a slot antenna microwave plasma source for hydrogen plasma cleaning PDF (402 kB) GZipped PS Order	D. Korzec, F. Werner, A. Brockhaus, J. Engemann, T. P. Schneider, and R. J. Nemanich	J. Vac. Sci. Technol. A **13**, 2074 (1995)
☐	77%	15.The coronal electron density distribution determined from dual-frequency ranging measurements during the 1991 solar conjunction of the Ulysses spacecraft Order	M. K. Bird, H. Volland, M. Pätzold, P. Edenhofer, S. W. Asmar, and J. P. Brenkle	Astrophys. J. **426**, 373 (1994)
☐	77%	16.Millimeter and submillimeter wave spectroscopy of HNC and DNC in the vibrationally excited states PDF (529 kB) GZipped PS Order	Toshiaki Okabayashi and Mitsutoshi Tanimoto	J. Chem. Phys. **99**, 3268 (1993)
☐	77%	17.Effects of magnetic fields and rotation on the fragmentation of filamentary molecular clouds: Comparison of the theory with the Orion A cloud Order	Tomoyuki Hanawa *et al.*	Astrophys. J. Lett. **404**, L83 (1993)

☐	77%	18.The structure of 3C 345 Order	L. I. Matveenko, D. A. Graham, I. I. K. Pauliny-Toth, W. A. Sherwood, L. B. Bääth, and A. Kus	Sov. Astron. Lett. **18**, 379 (1992)
☐	77%	19.Polarized radio emission from the edge-on spiral galaxies NGC 891 and NGC 4565 Order	S. Sukumar and R. J. Allen	Astrophys. J. **382**, 100 (1991)
☐	77%	20.VLBI observations of the nuclear jet in Cygnus A Order	Christopher L. Carilli, Norbert Bartel, and Roger P. Linfield	Astron. J. **102**, 1691 (1991)
☐	77%	21.Geometric optics in a tenuous energetic plasma PDF (871 kB) GZipped PS Order	R. K. Kirkwood	Phys. Fluids B **3**, 2741 (1991)
☐	77%	22.Nonclassical double-bridged structure in silicon-containing molecules: Experimental evidence in Si[sub 2]H[sub 2] from its submillimeter-wave spectrum [PROLA Link]	M. Bogey, H. Bolvin, C. Demuynck, and J. L. Destombes	Phys. Rev. Lett. **66**, 413 (1991)
☐	77%	23.The thermal, arched filaments of the radio arc near the Galactic center: Magnetohydrodynamic-induced ionization? Order	Mark Morris and Farhad Yusef-Zadeh	Astrophys. J. **343**, 703 (1989)
☐	77%	24.A six-electrode, direct-current, variable-length plasma source for atomic emission spectroscopy Order	James P. Shields, Gae Ho Lee, and Edward H. Piepmeier	Appl. Spectrosc. **42**, 684 (1988)
☐	77%	25.Plasmochemical applications of a discharge maintained by high-intensity millimeter electromagnetic radiation Order	Yu. V. Bykov, S. V. Golubev, A. L. Gol'denberg, and V. G. Zorin	Sov. Phys. Tech. Phys. **29**, 428 (1984)

1 2

Last Page

Article Collection: View Collection Help

AIP Publishing Center
Suite 1NO1, 2 Huntington Quadrangle, Melville, NY 11747-4502
For technical support: email, ojshelp@aip.org;
phone, 1-800-874-6383; fax, 516-576-2604 Privacy Policy

PATENT ABSTRACTS OF JAPAN

(11)Publication number : 2001-338918

(43)Date of publication of application : 07.12.2001

(51)Int.CI.

H01L 21/31
C23C 16/511
C23F 4/00
H01L 21/3065
H05H 1/46

(21)Application number : 2000-156535

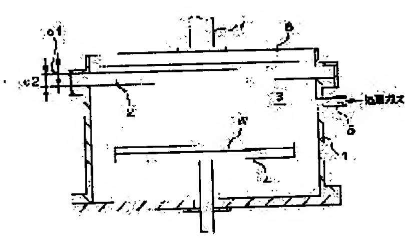
(22)Date of filing : 26.05.2000

(71)Applicant : OMI TADAHIRO
ROHM CO LTD

(72)Inventor : OMI TADAHIRO
INO KAZUHIDE
ARAKAWA TAKAHIRO

(54) APPARATUS FOR PLASMA TREATMENT

(57)Abstract:
PROBLEM TO BE SOLVED: To provide an apparatus for plasma treatment that can generate a high density plasma.
SOLUTION: The distance d1 between an under surface of a radial line slot antenna 6 and a top surface of a dielectric plate 2 is set at 6 mm and the thickness d2 of the dielectric plate 2 is set at 30 mm so that an interval D between the under surface of the radial line slot antenna 6 for expressing wavelengths of a microwave as a unit of a distance and the under surface of the dielectric plate 2 becomes approximately 1/2. As a result, good standing waves can be formed in the region between the under surface of the radial line slot antenna 6 and a plasma exciting surface, and the high density plasma can be generated in a processing space 3.



LEGAL STATUS

[Date of request for examination]

[Date of sending the examiner's decision of rejection]

[Kind of final disposal of application other than the examiner's decision of rejection or application converted registration]

[Date of final disposal for application]

[Patent number]

[Date of registration]

[Number of appeal against examiner's decision of rejection]

[Date of requesting appeal against examiner's decision of rejection]

[Date of extinction of right]

Day : Wednesday
Date: 9/4/2002
Time: 08:49:19

PALM INTRANET

Foreign Information for 09/864376

Priority#	Date	Country
2000-156535	05/26/2000	JAPAN

Appln Info | Contents | Petition Info | Atty/Agent Info | Continuity Data | **Foreign Data** | Inventors

Search Another: Application# [ ] Search **or Patent#** [ ] Search

PCT / [ ] / [ ] Search **or PG PUBS #** [ ] Search

Attorney Docket # [ ] Search

Bar Code # [ ] Search

To go back use Back button on your browser toolbar.

Back to PALM | ASSIGNMENT | OASIS | Home page

CLIPPEDIMAGE= JP02001338918A

PAT-NO: JP02001338918A

DOCUMENT-IDENTIFIER: JP 2001338918 A

TITLE: APPARATUS FOR PLASMA TREATMENT

PUBN-DATE: December 7, 2001

INVENTOR-INFORMATION:

NAME	COUNTRY
OMI, TADAHIRO	N/A
INO, KAZUHIDE	N/A
ARAKAWA, TAKAHIRO	N/A

ASSIGNEE-INFORMATION:

NAME	COUNTRY
OMI TADAHIRO	N/A
ROHM CO LTD	N/A

APPL-NO: JP2000156535

APPL-DATE: May 26, 2000

INT-CL (IPC): H01L021/31;C23C016/511 ;C23F004/00 ;H01L021/3065
;H05H001/46

ABSTRACT:

PROBLEM TO BE SOLVED: To provide an apparatus for plasma treatment that can
generate a high density plasma.

SOLUTION: The distance d1 between an under surface of a radial line slot antenna 6 and a top surface of a dielectric plate 2 is set at 6 mm and the thickness d2 of the dielectric plate 2 is set at 30 mm so that an interval D between the under surface of the radial line slot antenna 6 for expressing wavelengths of a microwave as a unit of a distance and the under surface of the

dielectric plate 2 becomes approximately 1/2. As a result, good standing waves can be formed in the region between the under surface of the radial line slot antenna 6 and a plasma exciting surface, and the high density plasma can be generated in a processing space 3.

(19)日本国特許庁（ＪＰ）

(12) 公開特許公報（Ａ）

(11)特許出願公開番号
特開2001－338918
（P2001－338918A）

(43)公開日 平成13年12月7日(2001.12.7)

(51)Int.Cl.⁷	識別記号	ＦＩ	テーマコード*(参考)
ＨＯ１Ｌ 21/31		ＨＯ１Ｌ 21/31	Ａ ４Ｋ０３０
Ｃ２３Ｃ 16/511		Ｃ２３Ｃ 16/511	４Ｋ０５７
Ｃ２３Ｆ 4/00		Ｃ２３Ｆ 4/00	Ｄ ５Ｆ００４
ＨＯ１Ｌ 21/3065		ＨＯ５Ｈ 1/46	Ｂ ５Ｆ０４５
ＨＯ５Ｈ 1/46		ＨＯ１Ｌ 21/302	Ｂ

審査請求 未請求 請求項の数３ ＯＬ （全 ７ 頁）

(21)出願番号 特願2000－156535(P2000－156535)

(22)出願日 平成12年5月26日(2000.5.26)

(71)出願人 000205041
大見 忠弘
宮城県仙台市青葉区米ケ袋２－１－17－301

(71)出願人 000116024
ローム株式会社
京都府京都市右京区西院溝崎町21番地

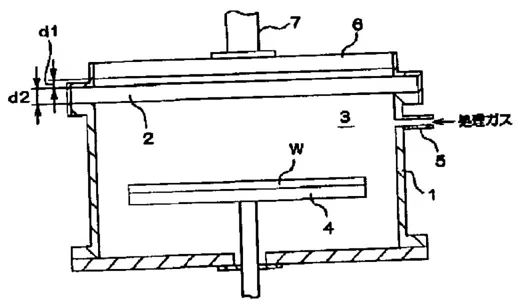
(72)発明者 大見 忠弘
宮城県仙台市青葉区米ケ袋２－１－17－301

(74)代理人 100087701
弁理士 稲岡 耕作 （外２名）

最終頁に続く

(54)【発明の名称】 プラズマ処理装置

(57)【要約】
【課題】高密度なプラズマを発生させることができるプラズマ処理装置を提供する。
【解決手段】マイクロ波の波長を距離単位として表すラジアルラインスロットアンテナ６の下面と誘電体板２の下面との間隔Ｄが約１／２となるように、ラジアルラインスロットアンテナ６の下面と誘電体板２の上面との間の距離ｄ１が６㎜に設定され、誘電体板２の厚みｄ２が３０㎜に設定されている。
【効果】ラジアルラインスロットアンテナ６の下面とプラズマ励起面との間の領域に良好な定在波を形成することができ、これにより、処理空間３内に高密度なプラズマを発生させることができる。



【特許請求の範囲】

【請求項１】被処理物および処理ガスが収容される処理空間にマイクロ波放射アンテナからマイクロ波を放射して、前記マイクロ波放射アンテナのマイクロ波放射面から所定距離だけ離れたプラズマ励起面でプラズマを励起し、その励起したプラズマを用いた処理を被処理物に施すプラズマ処理装置であって、

前記マイクロ波放射面に対向して誘電体が設けられており、

マイクロ波の波長を単位として表す前記マイクロ波放射面と前記誘電体の前記マイクロ波放射面に対向する面と反対側の面との間隔Dが、

０．７×ｎ／４≦Ｄ≦１．３×ｎ／４（ただし、ｎは自然数。）

の範囲に定められていることを特徴とするプラズマ処理装置。

【請求項２】前記間隔Dが０．７×ｎ／２≦Ｄ≦１．３×ｎ／２の範囲に定められていることを特徴とする請求項１記載のプラズマ処理装置。

【請求項３】前記マイクロ波放射アンテナは、マイクロ波を放射するための多数のスロットがマイクロ波放射面に分布して形成されたラジアルラインスロットアンテナであり、

前記処理空間内に発生するプラズマが面内均一となるように、前記多数のスロットの一部が塞がれていることを特徴とする請求項１または２記載のプラズマ処理装置。

【発明の詳細な説明】

【０００１】

【発明の属する技術分野】この発明は、たとえば半導体基板などの被処理物に、マイクロ波の放射により励起されたプラズマによる処理を施すプラズマ処理装置に関する。

【０００２】

【従来の技術】半導体装置の製造工程においては、ウエハ表面を窒化・酸化させて表面材質を変化させる表面改質処理やレジスト除去のためのアッシング処理、ウエハ表面に絶縁膜などの材料を堆積させて薄膜を形成する成膜処理や、ウエハ表面に形成された薄膜を微細パターンに加工するためのエッチング処理が行われる。このような処理のための装置として、ＲＬＳＡ（Radial Line Slot Antenna）プラズマ処理装置が注目されている。

【０００３】ＲＬＳＡプラズマ処理装置は、上面が開放された処理チャンバと、この処理チャンバの上面を閉塞するように設けられた誘電体板とを有しており、これらの処理チャンバおよび誘電体板で囲まれた空間が、被処理物としての半導体ウエハにプラズマ処理を施すための処理空間となっている。処理空間内には、半導体ウエハを載置して保持するためのウエハステージが設けられている。また、誘電体板の上方には、誘電体板を通して処理空間内にマイクロ波を放射するためのラジアルラインスロットアンテナが配置されている。

【０００４】たとえば、このＲＬＳＡプラズマ処理装置を用いて半導体ウエハの表面に窒化処理を施す際には、まず、半導体ウエハが、その表面を上方に向けた状態でウエハステージ上に載置される。次いで、処理空間内に処理ガス（たとえば、Ar/NH_3）が供給された後、ラジアルラインスロットアンテナから処理空間に向けてマイクロ波が放射される。これにより、処理空間内に処理ガスのプラズマが発生し、この発生したプラズマによって、ウエハステージに載置された半導体ウエハの表面が窒化処理されていく。

【０００５】ラジアルラインスロットアンテナは、下面全域に分布して形成された多数のスロットを有しており、これら多数のスロットからマイクロ波を放射するようになっている。したがって、このラジアルラインスロットアンテナを用いたＲＬＳＡプラズマ処理装置では、処理空間内にマイクロ波をほぼ均一に放射することができるから、処理ガスのプラズマを均一に発生させることができ、これにより半導体ウエハの表面に均一なプラズマ処理を施すことができると期待されている。

【０００６】

【発明が解決しようとする課題】ところが、従来のＲＬＳＡプラズマ処理装置は、処理空間内に発生するプラズマ密度が小さいために処理速度が遅く、半導体装置の製造に実際に用いることはできなかった。そこで、この発明の目的は、高密度なプラズマを発生させることができるプラズマ処理装置を提供することである。

【０００７】

【課題を解決するための手段および発明の効果】上記の目的を達成するための請求項１記載の発明は、被処理物および処理ガスが収容される処理空間にマイクロ波放射アンテナからマイクロ波を放射して、前記マイクロ波放射アンテナのマイクロ波放射面から所定距離だけ離れたプラズマ励起面でプラズマを励起し、その励起したプラズマを用いた処理を被処理物に施すプラズマ処理装置であって、前記マイクロ波放射面に対向して誘電体が設けられており、マイクロ波の波長を単位として表す前記マイクロ波放射面と前記誘電体の前記マイクロ波放射面に対向する面と反対側の面との間隔Ｄが、

０．７×ｎ／４≦Ｄ≦１．３×ｎ／４（ただし、ｎは自然数。）

の範囲（好ましくは０．８×ｎ／４≦Ｄ≦１．２×ｎ／４の範囲、さらに好ましくは０．９×ｎ／４≦Ｄ≦１．１×ｎ／４の範囲）に定められていることを特徴とするプラズマ処理装置である。

【０００８】なお、請求項２に記載のように、前記間隔Ｄは０．７×ｎ／２≦Ｄ≦１．３×ｎ／２の範囲（好ましくは０．８×ｎ／２≦Ｄ≦１．２×ｎ／２の範囲、さらに好ましくは０．９×ｎ／２≦Ｄ≦１．１×ｎ／２の範囲）に定められていることが好ましい。さらには、前

記マイクロ波放射面と前記プラズマ励起面との間にはマイクロ波の定在波が形成され、このマイクロ波の定在波からエネルギーの供給を受けることにより、前記プラズマ励起面においてプラズマが励起されることが好ましい。

【0009】上記の発明によれば、マイクロ波の波長を単位として表す前記マイクロ波放射面と前記プラズマ励起面との間隔Dが上記不等式で表された範囲（すなわち、n／4の近傍の値。さらに好ましくはn／2の近傍の値）に設定されることにより、マイクロ波放射面とプラズマ励起面との間の領域に良好な定在波を形成することができ、これにより、処理空間内に高密度なプラズマを発生させることができる。したがって、このプラズマ処理装置は、半導体装置を製造する工程などに好適に用いることができる。

【0010】なお、請求項3に記載のように、前記マイクロ波放射面と前記プラズマ励起面との間には誘電体板が介在されていることが好ましく、この場合において、誘電体板とマイクロ波放射面との間隔が微小であれば、誘電体板の厚みdを、

０．７×n／４≦d≦１．３×n／４（ただし、dはマイクロ波の波長を単位として表した厚さである。）

の範囲に定めてもよい。

【0011】請求項4記載の発明は、前記マイクロ波放射アンテナは、マイクロ波を放射するための多数のスロットがマイクロ波放射面に分布して形成されたラジアルラインスロットアンテナであり、前記処理空間内に発生するプラズマが面内均一となるように、前記多数のスロットの一部が塞がれていることを特徴とする請求項1ないし3のいずれかに記載のプラズマ処理装置である。この発明によれば、ラジアルラインスロットアンテナに形成されたスロットの一部を塞いで、ラジアルラインスロットアンテナから放射されるマイクロ波の強度分布を調整することにより、処理空間内に発生するプラズマ密度分布の面内均一化を、プラズマ密度の高密度化と同時に達成している。これにより、ほぼ均一なプラズマ処理を、従来装置よりも短時間で被処理物の表面に施すことができる。

【0012】

【発明の実施の形態】以下では、この発明の実施の形態を、添付図面を参照して詳細に説明する。図1は、この発明の一実施形態に係るプラズマ窒化装置の構成を示す図解的な断面図である。プラズマ窒化装置は、被処理物としての半導体ウエハWの表面を窒化物に改質するものであり、たとえば、Ｓｉ（シリコン）からなる半導体ウエハWの表面をSi_3N_4に変化させて絶縁層を形成する工程などに用いられる。

【0013】このプラズマ窒化装置は、上面が開放された有底筒状の処理チャンバ1を有している。処理チャンバ1の上部には、処理チャンバ1の開放された上面を閉

塞するように、たとえば石英からなる誘電体板2が設けられていて、これにより、誘電体板2の下方に密閉された処理空間3が形成されている。処理空間3内には、半導体ウエハWを載置して保持するためのウエハステージ4が配置されている。また、処理チャンバ1の側壁には、処理空間3内に処理ガスを導入するためのガス導入管5が接続されている。処理ガスとしては、たとえば、Ar/NH_3や$Ar/N_2/H_2$などを用いることができる。

【0014】誘電体板2の上方には、この誘電体板2の上面から距離ｄ１だけ離れた位置に、ラジアルラインスロットアンテナ6が誘電体板2の上面に対向して設けられている。ラジアルラインスロットアンテナ6は、内部にマイクロ波が伝搬可能な絶縁物のプレートを有する平板状アンテナであり、その下面には、図2に示すように、多数のスロットペアPが同心円状に配列して形成されている。各スロットペアPは、互いに交差する向きを有する一対のスロットＳ１，Ｓ２からなり、これらのスロットＳ１，Ｓ２は、ラジアルラインスロットアンテナ6内におけるマイクロ波波長の１／４に相当する距離（１／４管内波長＝１／４λｇ）だけ離間して略Ｔ字状をなしている。

【0015】一方、ラジアルラインスロットアンテナ6の上面には、図示しないマイクロ波発振器から発振されるマイクロ波を絶縁物プレートに導くための導波管7が接続されている。この導波管7としては、たとえば、同軸導波管を用いることができる。半導体ウエハWの表面に窒化処理を施す際には、まず、半導体ウエハWが、その表面を上方に向けた状態でウエハステージ4上に載置される。次いで、図示しない排気機構によって処理空間3内の雰囲気が排気され、処理空間3内がほぼ真空状態にされた後、この処理空間3内にガス導入管5から処理ガス（プロセスガス）が導入される。その後、処理空間3内に処理ガスが充満した状態で、たとえば、図示しないマイクロ波発振器から周波数２．４５GHzのマイクロ波が発振され、このマイクロ波がTEMモードで導波管7内を伝搬してラジアルラインスロットアンテナ6内に導入される。

【0016】ラジアルラインスロットアンテナ6内に導入されたマイクロ波は、ラジアルラインスロットアンテナ6内の絶縁物プレートを伝搬し、その途中でスロットペアPから漏れて誘電体板2に向けて放射され、さらに誘電体板2を透過して処理空間3に放射される。この処理空間3に放射されるマイクロ波のエネルギーにより、処理空間3内に処理ガスのプラズマが励起され、その処理ガスのプラズマによる処理が半導体ウエハWの表面に施されていく。

【0017】ところで、処理空間3内に発生したプラズマ中の電子密度がマイクロ波を遮蔽可能な密度（カットオフ密度）以上になると、誘電体板2を透過してくるマ

イクロ波は、誘電体板２の下面から処理空間３内に微小距離（スキンデプス）だけ入るまでの間に反射されるようになる。その結果、ラジアルラインスロットアンテナ６の下面（マイクロ波放射面）とマイクロ波の反射端が形成する面（マイクロ波反射面）との間の領域にマイクロ波の定在波が形成され、この後は、マイクロ波反射面がプラズマ励起面となって、このプラズマ励起面で安定なプラズマが励起されるようになる。

【００１８】したがって、プラズマ中の電子密度がカットオフ密度以上になると、処理空間３内に発生するプラズマの密度は、ラジアルラインスロットアンテナ６の下面とプラズマ励起面との間に形成される定在波の状態の影響を受けると考えられる。そして、本願発明者らは、ラジアルラインスロットアンテナ６の下面と誘電体板２の下面との距離を適切に設定して、ラジアルラインスロットアンテナ６の下面とプラズマ励起面との間の領域に良好な定在波を形成することにより、処理空間３内に発生するプラズマの密度を高めることができると考えた。

【００１９】すなわち、従来のＲＬＳＡプラズマ処理装置では、ラジアルラインスロットアンテナの下面と誘電体板２の下面との間隔がマイクロ波の波長と無関係に設定されているのに対し、このプラズマ窒化装置（プラズマ処理装置）では、マイクロ波の波長を距離単位として表すラジアルラインスロットアンテナ６の下面と誘電体板２の下面（≒プラズマ励起面）との間隔Ｄが約１／２となるように、ラジアルラインスロットアンテナ６の下面と誘電体板２の上面との間の距離ｄ１および誘電体板２の厚みｄ２が設定されている。この実施形態では、たとえば、ラジアルラインスロットアンテナ６の下面と誘電体板２の上面との間の距離ｄ１が６㎜に設定され、誘電体板２の厚みｄ２が３０㎜に設定されている。

【００２０】ここで、マイクロ波の波長を距離単位として表すラジアルラインスロットアンテナ６の下面と誘電体板２の下面との間隔Ｄは、空気中におけるマイクロ波の波長をλ0とし、誘電体板２中におけるマイクロ波の波長をλとすると、

$$D=(d1/\lambda 0)+(d2/\lambda)$$

と表される。誘電体板２中におけるマイクロ波の波長λは、誘電体板２の比誘電率をε_rとすると、

【００２１】

【数１】

$$\lambda=\lambda_0/\sqrt{\varepsilon_r}$$

【００２２】と表されるから、上記間隔Ｄは、

【００２３】

【数２】

$$D=(d1+d2\sqrt{\varepsilon_r})/\lambda_0$$

【００２４】と表すことができる。したがって、この実施形態では、石英からなる誘電体板２の非誘電率ε_r＝３．９および周波数２．４５GHzのマイクロ波の空気中（真空中）における波長λ0＝１２２(㎜)を上記式(1)に代入することにより、マイクロ波の波長を距離単位として表すラジアルラインスロットアンテナ６の下面と誘電体板２の下面との間隔Ｄが約０．５３に設定されていることが判る。図３は、(a)誘電体板２の厚みｄ２を３０㎜に設定した場合、および(b)誘電体板２の厚みｄ２を２０㎜に設定した場合（従来装置）の半導体ウエハＷの表面に入射するイオン電流密度分布を示すグラフである。いずれのグラフも、ラジアルラインスロットアンテナ６の下面と誘電体板２の上面との間の距離ｄ１を６㎜に、誘電体板２の下面と半導体ウエハＷの表面との間の距離を６５㎜に、処理空間３内の気圧を６６．５Paにそれぞれ設定して、ラジアルラインスロットアンテナ６に周波数２．４５GHzで電力１２００Ｗのマイクロ波を導入して励起させたプラズマ中のイオン電流密度分布を調べた結果を示している。

【００２５】図３(a)(b)の比較から、誘電体板２の厚みｄ２を３０㎜に設定した場合の方が、誘電体板２の厚みｄ２を２０㎜に設定した場合よりも、半導体ウエハＷの表面におけるイオン電流密度（プラズマ密度）が大きいことが理解される。ところが、誘電体板２の厚みｄ２を２０㎜に設定した場合は、半導体ウエハＷの表面におけるイオン電流密度の分布がほぼ均一であるのに対し、誘電体板２の厚みｄ２を３０㎜に設定した場合は、半導体ウエハＷの中心付近に入射するイオン電流が半導体ウエハＷの周縁付近に入射するイオン電流よりも大きくなっており、イオン電流密度の分布に面内不均一が生じている。

【００２６】そこで、この実施形態では、ラジアルラインスロットアンテナ６の下面に形成されているスロットペアＰの一部を塞ぎ、ラジアルラインスロットアンテナ６から放射されるマイクロ波の強度分布を調整することにより、半導体ウエハＷの表面に入射するイオン電流密度分布の均一化を図っている。具体的には、ラジアルラインスロットアンテナ６の下面の最外周に配列されたスロットペアＰの１／６または１／３を塞ぐことにより、半導体ウエハＷの表面に入射するイオン電流密度分布の均一化を図っている。

【００２７】なお、１／６のスロットペアＰを塞ぐとは、周方向に沿って６個に１個の割合でスロットペアＰを塞ぐことをいい、１／３のスロットペアＰを塞ぐとは、周方向に沿って３個に１個の割合でスロットペアＰを塞ぐことをいう。図４は、(a)スロットペアＰを１つも塞がなかった場合、(b)最外周に配列されたスロットペアＰのうちの１／６を塞いだ場合、および(c)最外周に配列されたスロットペアＰのうちの１／３を塞いだ場合の半導体ウエハＷの表面に入射するイオン電流密度分布を示すグラフである。いずれのグラフも、ラジアルラインスロットアンテナ６の下面と誘電体板２の上面との

間の距離ｄ１を６㎜に、誘電体板２の厚みｄ２を３０㎜に、誘電体板２の下面と半導体ウエハＷの表面との間の距離を６５㎜に、処理空間３内の気圧を６６．５Paにそれぞれ設定して、ラジアルラインスロットアンテナ６に周波数２．４５GHzで電力１２００Ｗのマイクロ波を導入して励起させたプラズマ中のイオン電流密度分布を調べた結果を示している。

【００２８】この図４から、最外周に配列されたスロットペアＰのうちの１／６個または１／３個を塞ぐことにより、半導体ウエハＷの表面に入射するイオン電流密度分布が均一化されることが理解される。以上のようにこの実施形態によれば、マイクロ波の波長を距離単位として表すラジアルラインスロットアンテナ６の下面と誘電体板２の下面との間隔Ｄが約１／２となるように、ラジアルラインスロットアンテナ６の下面と誘電体板２の上面との間の距離ｄ１および誘電体板２の厚みｄ２を上手く設定することにより、処理空間３内に発生するプラズマの高密度化を達成している。したがって、このプラズマ窒化装置は、半導体ウエハＷの表面に窒化処理を施して半導体装置を製造する工程に好適に用いることができる。

【００２９】また、この実施形態では、ラジアルラインスロットアンテナ６の下面に形成されたスロットパターンＰの一部を塞いで、ラジアルラインスロットアンテナ６から放射されるマイクロ波の強度分布を調整することにより、ウエハステージ４に載置された半導体ウエハＷの表面に入射するイオン電流密度分布の均一化を、イオ＊ン電流（プラズマ密度）の高密度化と同時に達成している。これにより、ほぼ均一なプラズマ窒化処理を、従来装置よりも短時間で半導体ウエハＷの表面に施すことができる。

【００３０】なお、この実施形態では、誘電体板２を石英で構成して、ラジアルラインスロットアンテナ６の下面と誘電体板２の上面との間の距離ｄ１を６㎜に設定し、誘電体板２の厚みｄ２を３０㎜に設定する場合を例に挙げたが、誘電体板２は、たとえばアルミナ（Al_2O_3）またはアルミナイトライド（ＡｌＮ）など、石英以外の誘電体で構成されていてもよい。また、上記距離ｄ１および厚みｄ２の値も適当に変更されるとよく、たとえば、誘電体板２が熱伝導率の大きい材料で構成されて、プラズマ中のイオンと電子とが再結合して発生する熱を効率よくチャンバ壁に伝達することによりラジアルラインスロットアンテナ６の高温化を防止できる場合には、ラジアルラインスロットアンテナ６の下面と誘電体板２の上面との間の距離ｄ１が０㎜に設定されて、ラジアルラインスロットアンテナ６が誘電体板２に接触していてもよい。

【００３１】誘電体板２の材料と、マイクロ波の波長を距離単位として表すラジアルラインスロットアンテナ６の下面と誘電体板２の下面との間隔Ｄが約１／２となる上記距離ｄ１および厚みｄ２との組み合わせの例を下記表にまとめておく。

【００３２】

【表１】

誘電体板の材料	距離ｄ１	厚みｄ２
石英（比誘電率＝３．９）	０㎜	３０．９㎜
	１．８㎜	３０㎜
アルミナイトライド（比誘電率＝８．８）	０㎜	２０．６㎜
	４．６㎜	１９㎜
アルミナ（比誘電率＝９．８）	０㎜	１９．５㎜
	４．７㎜	１８㎜

【００３３】また、この実施形態では、マイクロ波の波長を距離単位として表すラジアルラインスロットアンテナ６の下面と誘電体板２の下面との間隔Ｄが約１／２となるように、ラジアルラインスロットアンテナ６の下面と誘電体板２の上面との間の距離ｄ１および誘電体板２の厚みｄ２を設定することが好ましいとしたが、たとえば、上記間隔Ｄが約１／２の整数倍となるように、上記距離ｄ１および厚みｄ２が設定されてもよい。さらには、上記間隔Ｄが約１／４の整数倍となるように、上記距離ｄ１および厚みｄ２が設定されてもよい。

【００３４】すなわち、ラジアルラインスロットアンテナ６の下面とプラズマ励起面との間の領域に良好な定在波を形成して、処理空間３内に高密度なプラズマを発生させるためには、マイクロ波の波長を距離単位として表すラジアルラインスロットアンテナ６の下面と誘電体板２の下面との間隔Ｄが次の不等式を満たせばよい。

※$0.7 \times n/4 \leq D \leq 1.3 \times n/4$（ｎ：自然数）

さらに、この発明は他の形態で実施することもできる。たとえば、上述の実施形態では、プラズマ窒化装置を例にとって説明したが、このプラズマ窒化装置に限定されず、たとえばプラズマＣＶＤ（Chemical Vapor Deposition）装置やプラズマアッシング装置、プラズマエッチング装置、プラズマ酸化装置など、被処理物にプラズマによる処理を施す装置に広く本発明を適用することができる。

【００３５】なお、この発明がプラズマＣＶＤ装置に適用される場合には、処理ガスとして、たとえばAr/SiH_4や$TEOS/O_2$などを用いることができる。また、この発明がプラズマアッシング装置に適用される場合には、処理ガスとして、たとえばO_2、Ar/O_2またはKr/O_2などを用いることができる。さらに、この発明がプラズマエッチング装置に適用される場合には、

処理ガス（エッチングガス）として、たとえばCl_2やＨＢｒなどを用いることができる。さらにまた、この発明がプラズマ酸化装置に適用される場合には、処理ガスとして、たとえばKr/O_2やAr/O_2などを用いることができる。

【００３６】その他、特許請求の範囲に記載された事項の範囲で種々の変更を施すことが可能である。

【図面の簡単な説明】

【図１】この発明の一実施形態に係るプラズマ窒化装置の構成を示す図解的な断面図である。

【図２】ラジアルラインスロットアンテナの下面を示す図である。

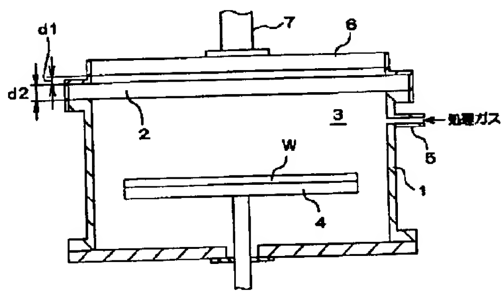
【図３】(a)誘電体板の厚みを３０㎜に設定した場合、および(b)誘電体板の厚みを２０㎜に設定した場合（従来装置）の半導体ウエハの表面に入射するイオン電流密度分布を示すグラフである。

【図４】(a)スロットペアを１つも塞がなかった場合、(b)最外周に配列されたスロットペアのうちの１／６を塞いだ場合、および(c)最外周に配列されたスロットペアのうちの１／３を塞いだ場合の半導体ウエハの表面に入射するイオン電流密度分布を示すグラフである。

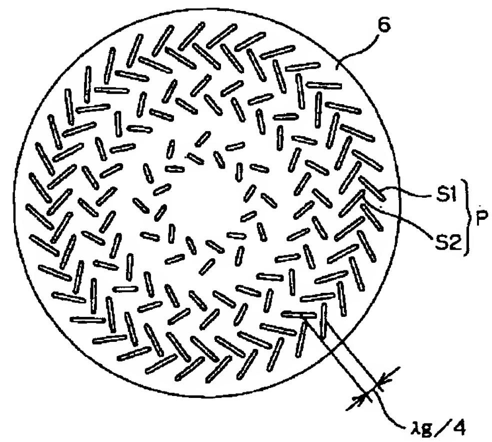
【符号の説明】

1　処理チャンバ
2　誘電体板
3　処理空間
4　ウエハステージ
5　ガス導入管
6　ラジアルラインスロットアンテナ（マイクロ波放射アンテナ）
7　導波管
P　スロットペア
S1，S2　スロット
W　半導体ウエハ（被処理物）

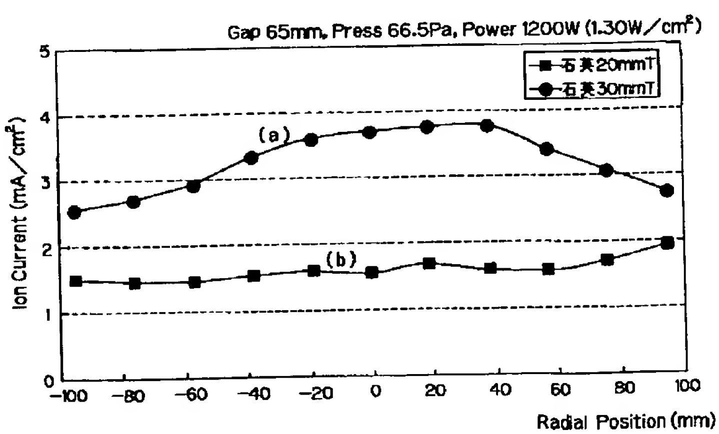
【図１】



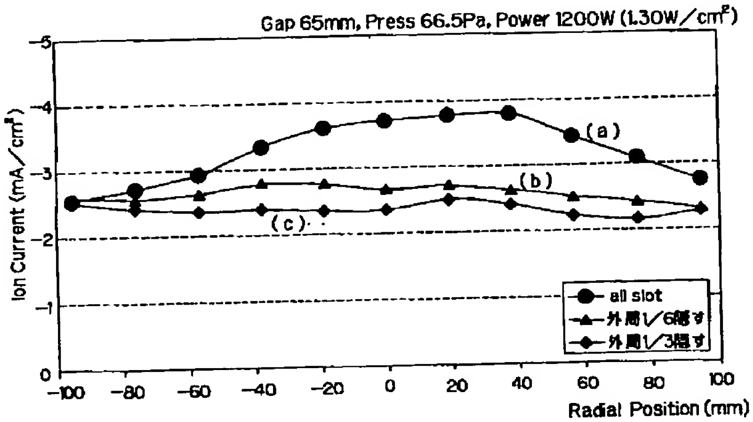
【図２】



【図３】



【図4】



フロントページの続き

(72)発明者　伊野　和英
京都市右京区西院溝崎町21番地　ローム株式会社内

(72)発明者　荒川　貴博
京都市右京区西院溝崎町21番地　ローム株式会社内

Fターム(参考)　4K030 FA01 JA03 KA30
4K057 DA16 DB06 DD01 DE14 DM02 DM29 DN01
5F004 BA20 BC08 BD01 BD04 DA00 DA04 DA23 DA26
5F045 AA09 AA20 AB33 AC12 AC16 AC18 BB09 DP04 EH02 EH11

US006376796B2

(12) United States Patent
Sato et al.

(10) Patent No.: US 6,376,796 B2
(45) Date of Patent: Apr. 23, 2002

(54) PLASMA PROCESSING SYSTEM

(75) Inventors: Noriyoshi Sato, 4-17-113, Kadan, Aoba-ku; Satoru Iizuka, 6-5-10-201, Koriyama; Tsukasa Yoneyama, 12-17, Aza Kodaira, Hukurohara, both of Taihaku-ku; Hiroyasu Sato, 2-1-5, Aoyama, Taihaku-ku, all of Sendai-shi, Miyagi-ken; Unryu Ogawa; Yoshio Tominaga, both of Tokyo; Yoichiro Numazawa, Machida; Yukito Nakagawa, Tachikawa, all of (JP)

(73) Assignees: Noriyoshi Sato; Satoru Iizuka; Tsukasa Yoneyama; Hiroyasu Sato, all of Sendai; Anelva Corporation; Hitachi Kokusai Electric, Inc., both of Tokyo, all of (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: 09/738,989

(22) Filed: Dec. 19, 2000

(30) Foreign Application Priority Data

Dec. 20, 1999 (JP) 11-360929

(51) Int. Cl.[7] B23K 9/02

(52) U.S. Cl. 219/121.43; 219/121.36; 373/25

(58) Field of Search .... 219/121.41, 121.43, 219/121.59, 121.11, 121.36, 121.39, 121.4; 204/298.18, 298.19, 298.37, 298.38; 156/345; 118/723 MN, 723 I, 723 E; 373/18, 25

(56) References Cited

U.S. PATENT DOCUMENTS

6,033,481 A * 3/2000 Yokogawa et al. 118/723
6,034,346 A * 3/2000 Yoshioka et al. 219/121.43
6,051,114 A * 4/2000 Yao et al. 204/192.3

FOREIGN PATENT DOCUMENTS

JP 06-325899 11/1994
JP 09-19901 7/1997

OTHER PUBLICATIONS

Sato et al., "Uniform Plasma Produced by a Plane Slotted Antenna With Magnets For Electron Cyclotron Resonance" Appl. Phys. Lett., 62 (1993) 1469.

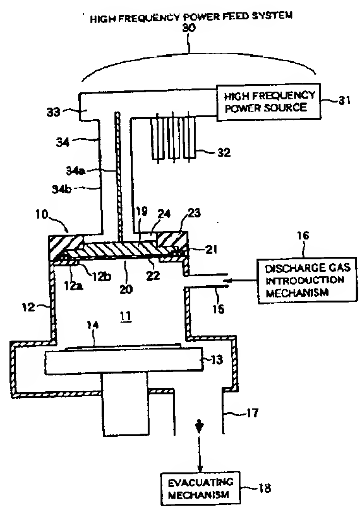
* cited by examiner

Primary Examiner—Tu Ba Hoang
(74) *Attorney, Agent, or Firm*—Oliff & Berridge, PLC

(57) ABSTRACT

A plasma processing system provided with a vacuum chamber for accommodating a substrate and for generation of plasma in a space in the front of the same, an antenna provided at the vacuum chamber, and a high frequency power source for supplying high frequency power to the antenna. The antenna emits high frequency power, generates plasma inside the vacuum chamber, and processes the surface of the substrate by the plasma. In the plasma processing system, the antenna has a disk-shaped conductor plate having a predetermined thickness. A coaxial waveguide having a folded portion is formed around the disk-shaped conductor plate. The folded portion of the waveguide is provided with a short-circuit 3 dB directional coupler having an impedance matching function. The antenna having the above structure prevents the generation of a standing wave in the high frequency wave propagation path from the high frequency power source to the vacuum chamber and generates high density plasma by supply of a large power. Due to this, processing of a large area substrate becomes possible.

9 Claims, 7 Drawing Sheets



09/04/2002, EAST Version: 1.03.0002

FIG. 1

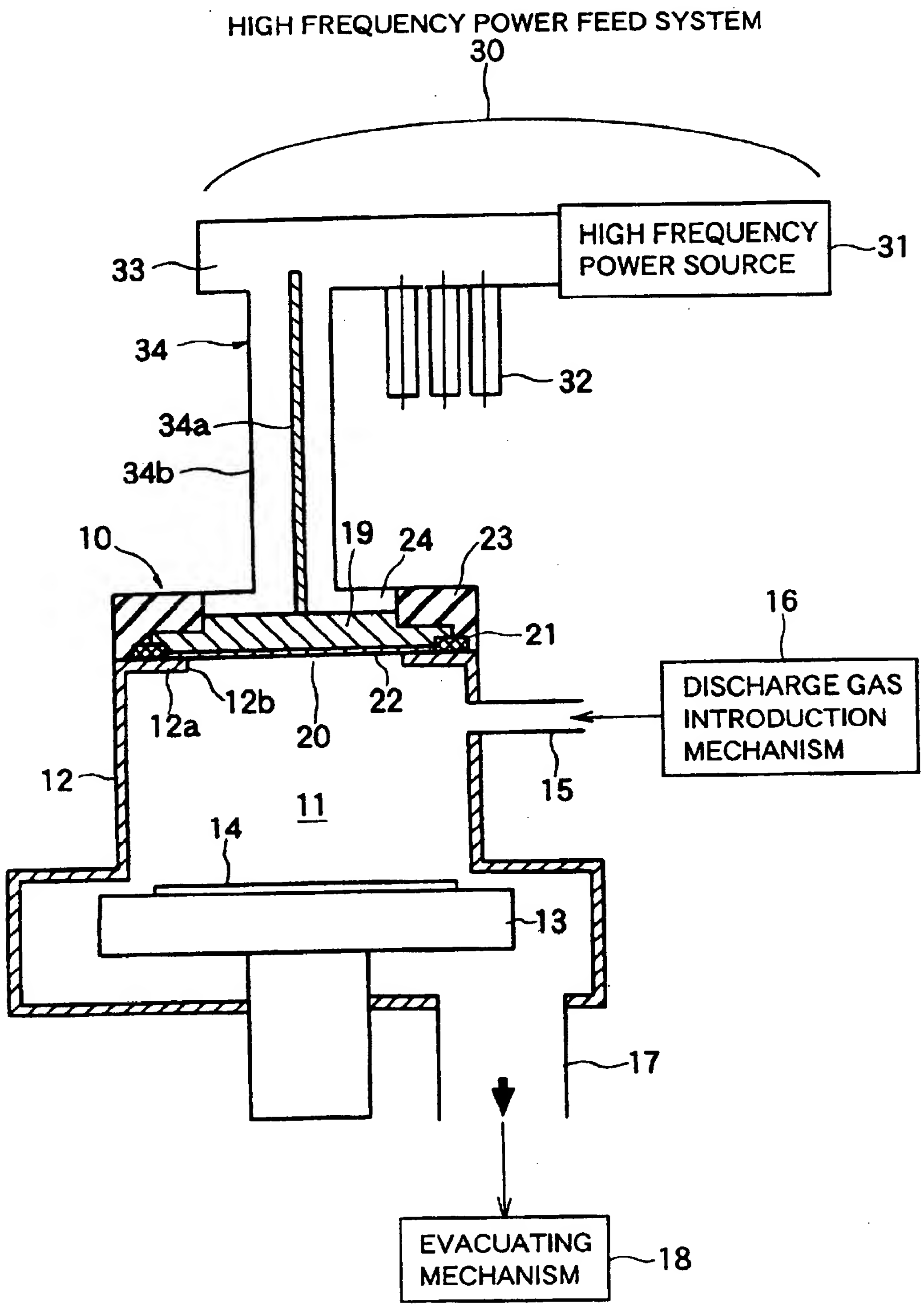

HIGH FREQUENCY POWER FEED SYSTEM
30
HIGH FREQUENCY POWER SOURCE
31
33
34
32
34a
34b
10
19
24
23
21
16
12b
22
DISCHARGE GAS INTRODUCTION MECHANISM
12a
20
12
15
11
14
13
17
EVACUATING MECHANISM
18

FIG. 2

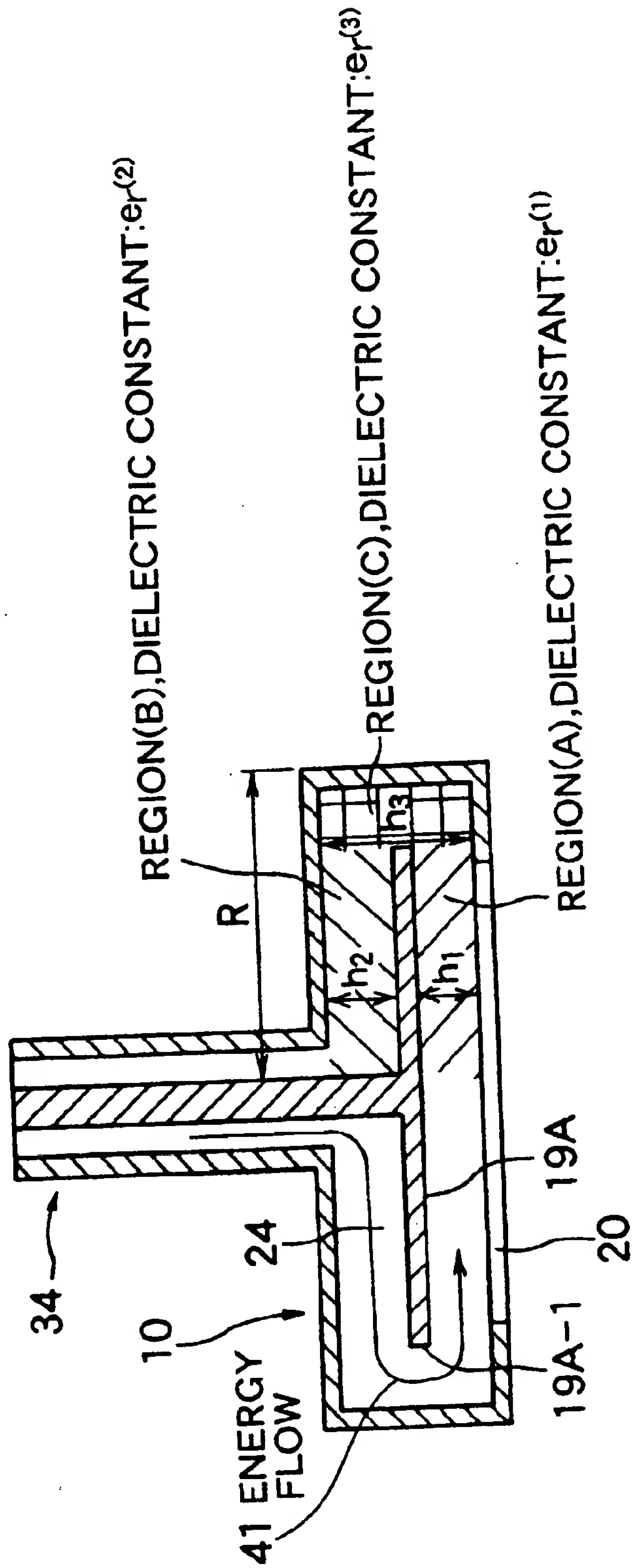
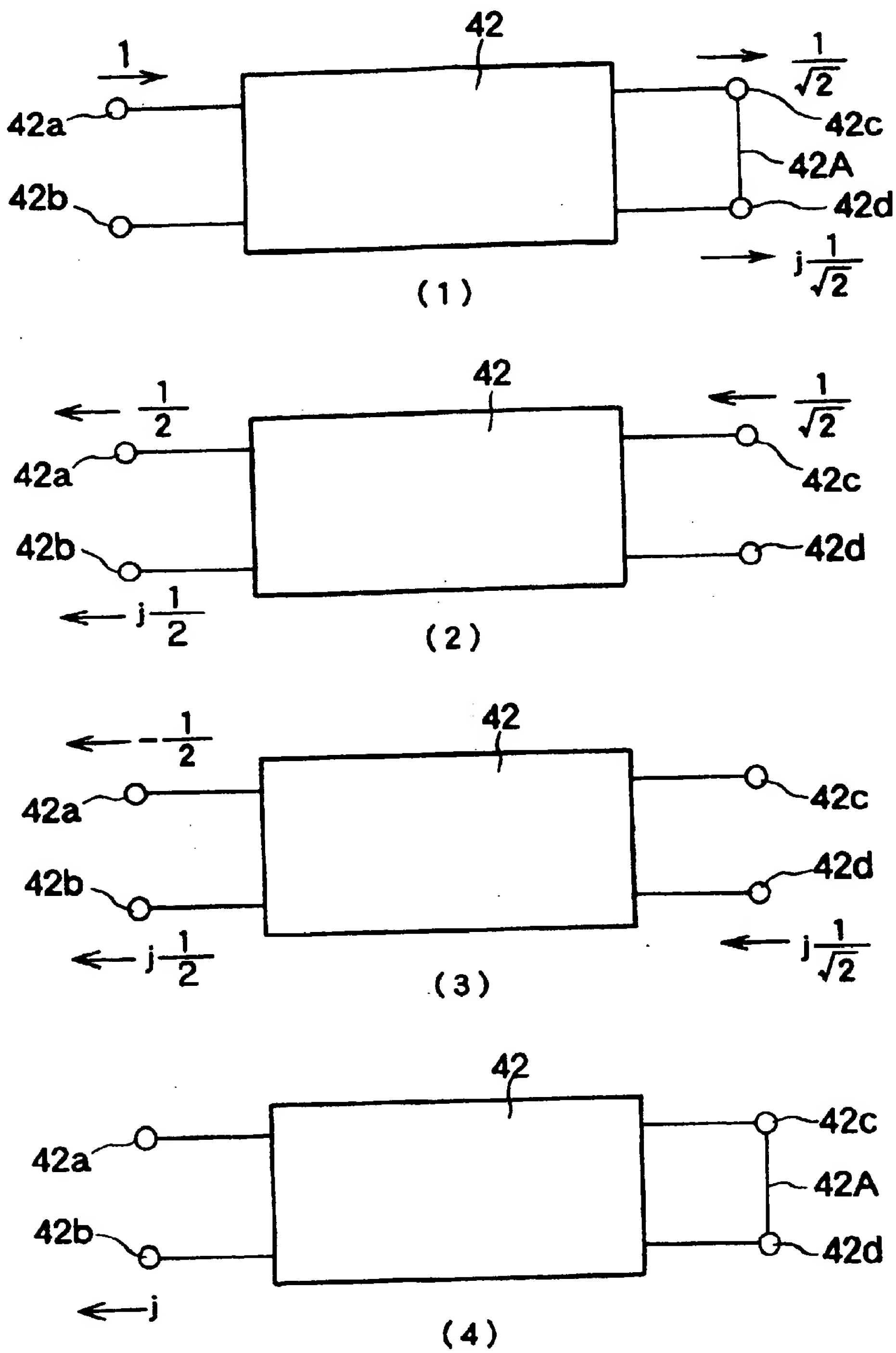

REGION(B),DIELECTRIC CONSTANT:$e_r^{(2)}$
REGION(C),DIELECTRIC CONSTANT:$e_r^{(3)}$
REGION(A),DIELECTRIC CONSTANT:$e_r^{(1)}$
R
h_3
h_2
h_1
34
10
24
19A
20
19A-1
41 ENERGY FLOW

FIG. 3



42
1
1/√2
42a
42c
42A
42b
42d
j 1/√2
(1)
42
1/2
1/√2
42a
42c
42b
42d
j 1/2
(2)
42
-1/2
42a
42c
42b
42d
j 1/2
j 1/√2
(3)
42
42a
42c
42A
42b
42d
j
(4)

FIG. 4

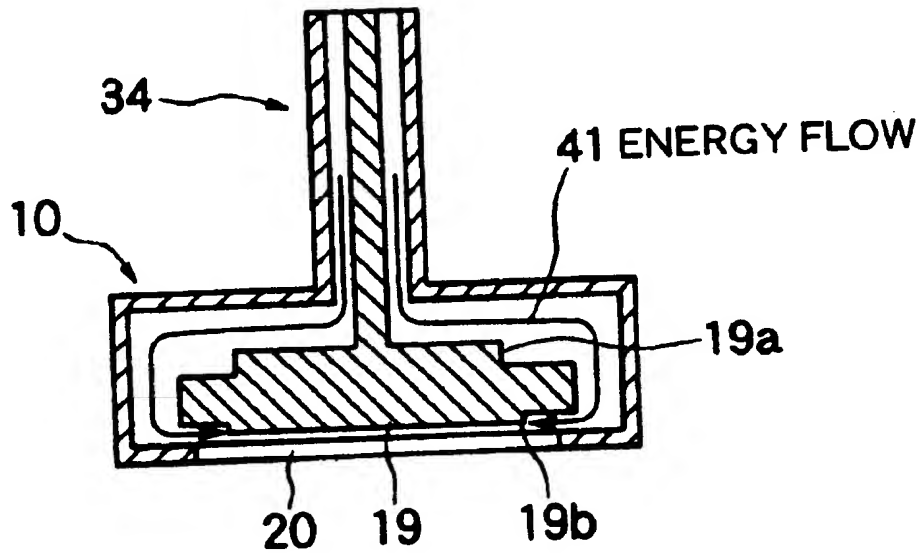


FIG. 5

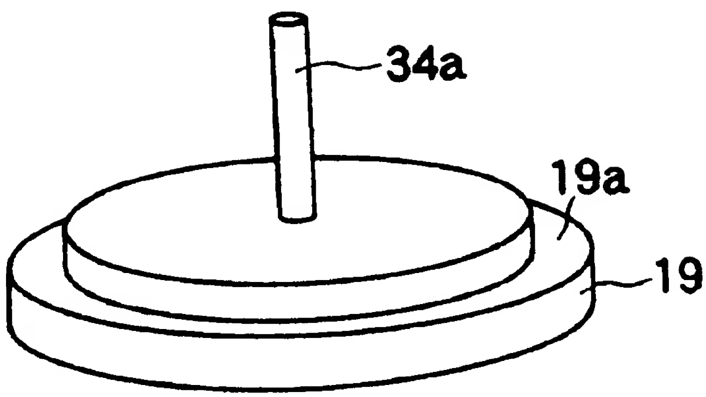


FIG. 6

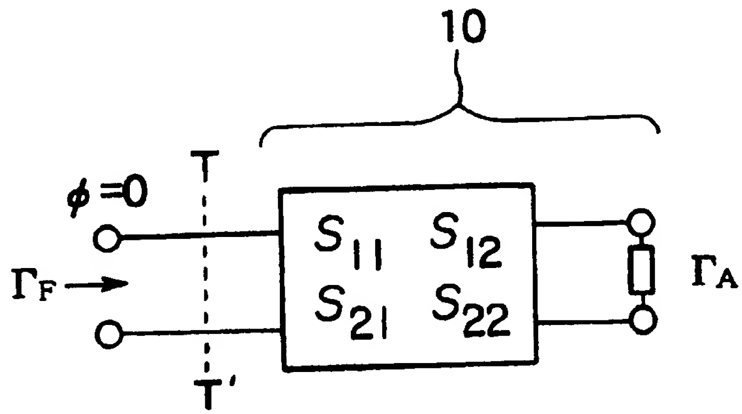

10
T
T'
ϕ=0
Γ_F
S_{11} S_{12}
S_{21} S_{22}
Γ_A

FIG. 7

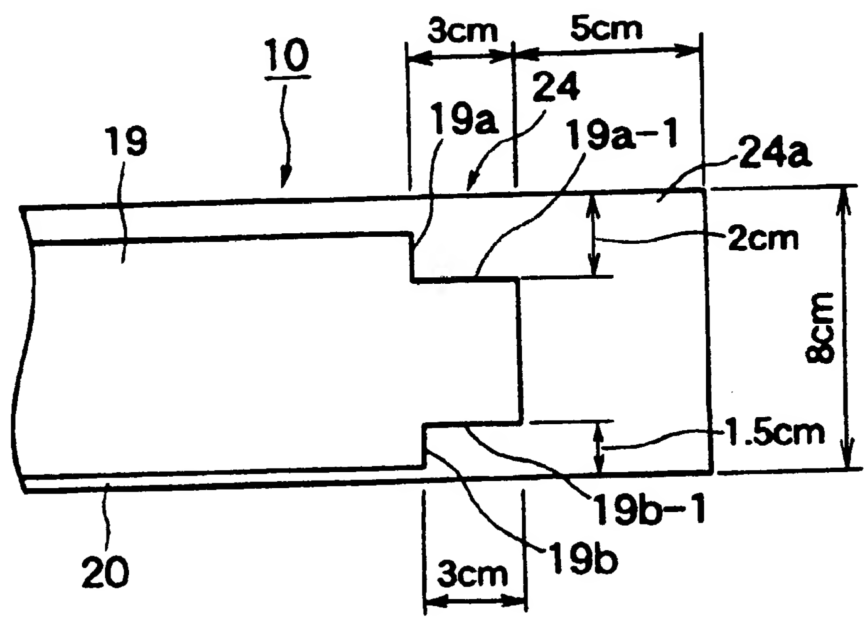

3cm
5cm
10
24
19a
19a-1
24a
19
2cm
8cm
1.5cm
19b-1
19b
20
3cm

FIG. 8

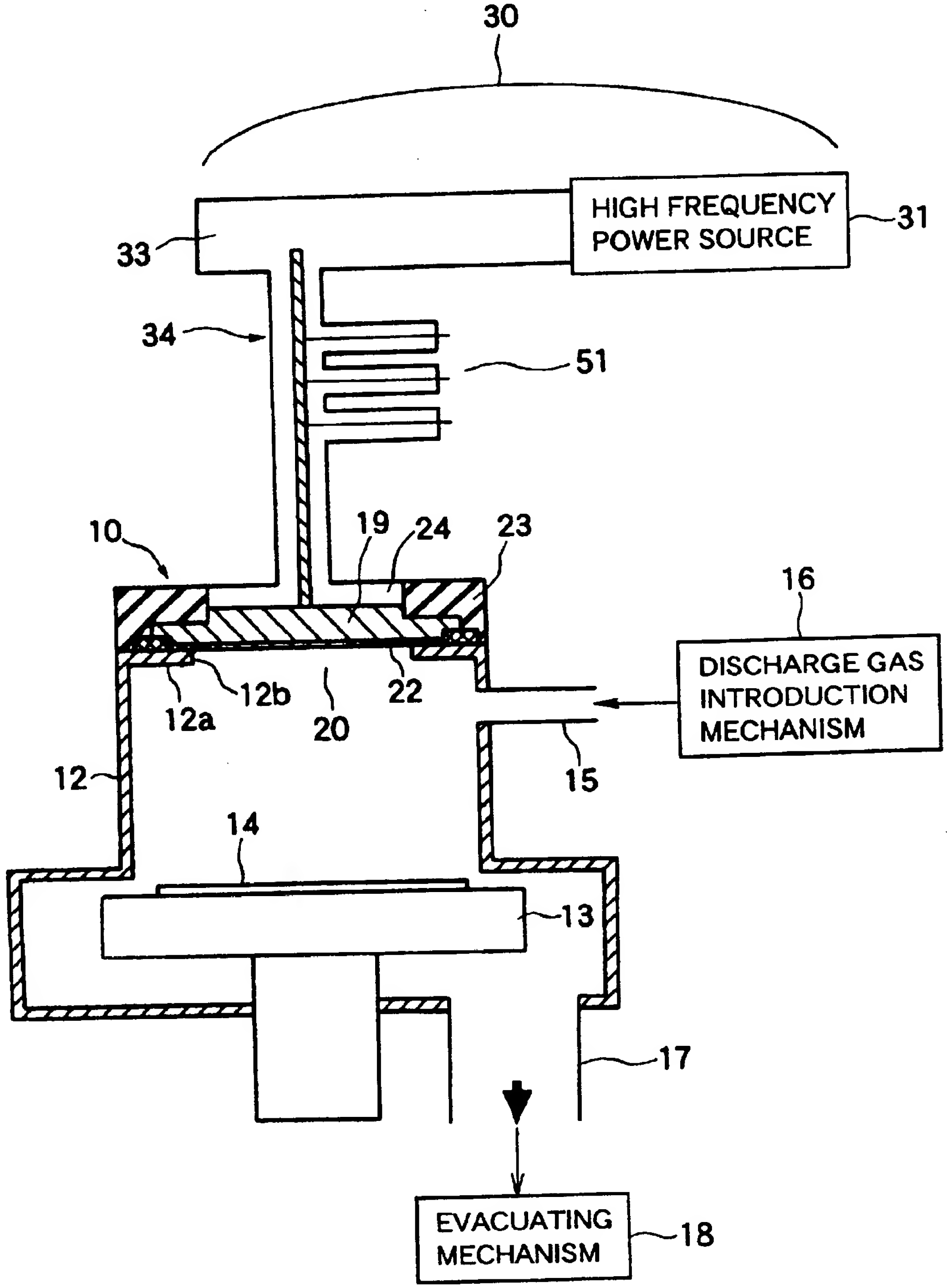
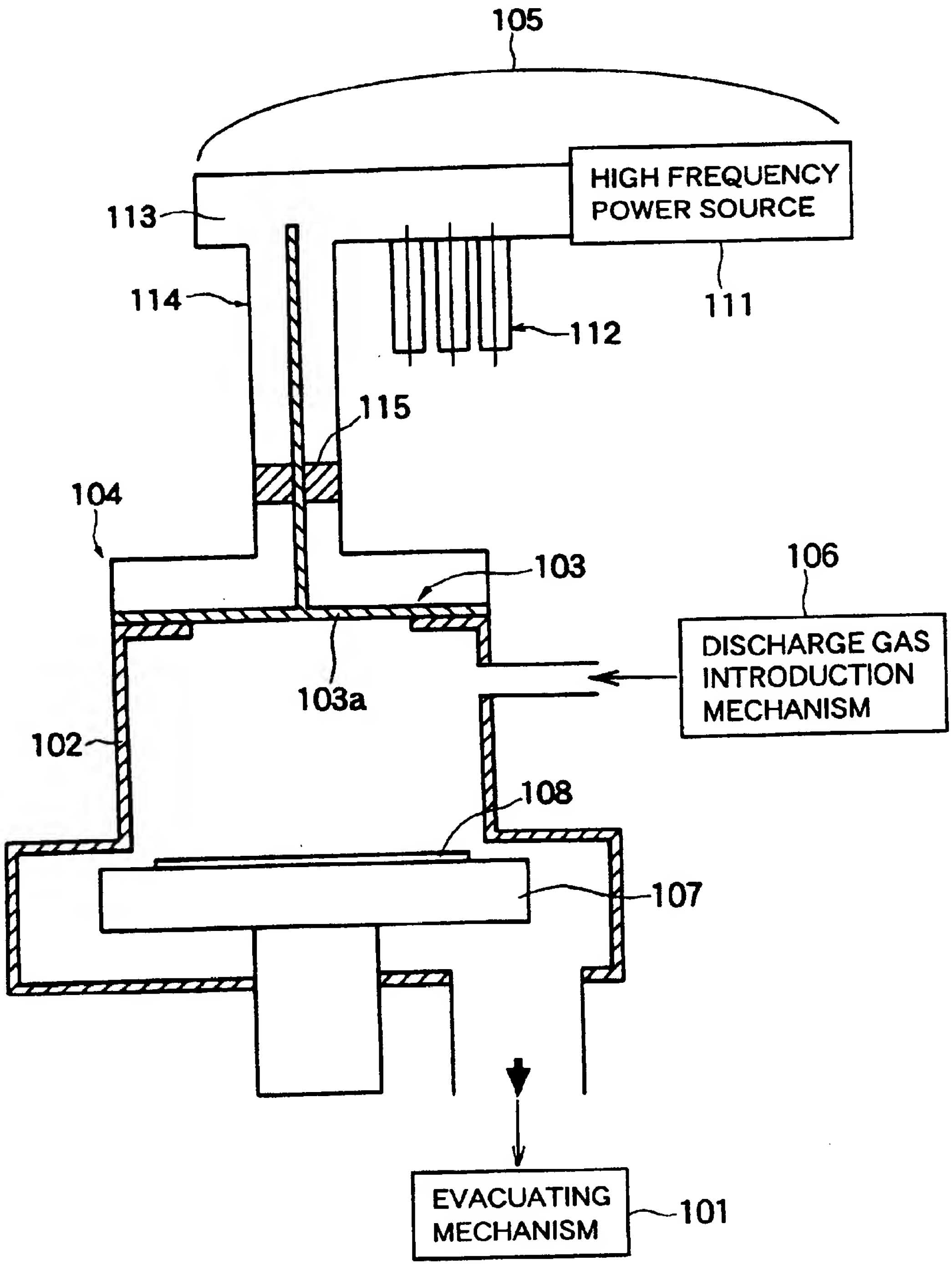

30
HIGH FREQUENCY POWER SOURCE
31
33
34
51
10
19
24
23
16
DISCHARGE GAS INTRODUCTION MECHANISM
12a
12b
20
22
12
15
14
13
17
EVACUATING MECHANISM
18

FIG. 9


105
HIGH FREQUENCY POWER SOURCE
113
114
111
112
115
104
103
106
103a
DISCHARGE GAS INTRODUCTION MECHANISM
102
108
107
EVACUATING MECHANISM
101

PLASMA PROCESSING SYSTEM

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a plasma processing system, and more particularly, relates to an antenna supplying a large power and useful for generation of high density plasma without causing any loss and a plasma processing system efficiently generating high density plasma using the antenna and performing predetermined processing on the surface of a substrate.

2. Description of the Related Art

Among the systems for performing predetermined processing on the surface of a semiconductor wafer or liquid crystal substrate (hereinafter referred to as a "substrate") using plasma, plasma enhanced chemical vapor deposition (PCVD) and plasma etching systems are widely known. In these plasma processing systems, it is necessary to generate high density plasma in order to increase the processing rate. In addition, from the viewpoint of preventing impurities, it is required to form high density plasma by a lower pressure.

To generate plasma for the surface processing, from the viewpoint of obtaining high density plasma with a high efficiency, a system using the gaseous discharge generated by high frequency power is used. The inventors of the present patent application have already proposed a plasma processing system of a type supplying a high frequency power of 2.45 GHz to a radial slotted antenna connected to a coaxial high frequency power feed system to generate plasma (Japanese Patent No. 8-2534219) and have confirmed that good plasma processing was possible (as document, see for example N. Sato et al., "Uniform Plasma Produced by a Plane Slotted Antenna With Magnets For Electron Cyclotron Resonance" for the configuration of a plasma processing system using a slotted antenna shown in the above document. This plasma processing system has a vacuum chamber **102** provided with an evacuating mechanism **101** and generating a discharge inside for generation of plasma, an antenna device **104** arranged on the upper section of the vacuum chamber **102** and provided with a slotted antenna **103**, a high frequency wet-feed system **105** for feeding high frequency power to the slotted antenna **103**, a discharge gas introduction mechanism **105** for introducing a discharge gas into the vacuum chamber **102**, and a substrate holder **107** arranged at a lower position inside the vacuum chamber **102**. A substrate **108** is loaded on the substrate holder **107** as an object to be processed. The shape of the slots (or slits) formed in the slotted antenna **103** is explained in detail in the above-mentioned patent specification or document. The slotted antenna **103** is actually provided with a magnetic circuit formed by permanent magnets etc. for generating a magnetic field near the electromagnetic wave emitter **103***a*, but in FIG. **9**, its illustration is omitted. Further, as a result of the addition of the magnetic circuit, the slotted antenna **103** originally to be produced as the disk-shaped conductor plate is actually produced as a conductor having a predetermined thickness being able to house a magnetic circuit. In FIG. **9**, however, for convenience of explanation, it is shown as a plate material. The high frequency power feed system **104** supplying the high frequency power is comprised of a high frequency power source **111**, a stub tuner **112**, a coaxial waveguide converter **113**, a coaxial line **114**, and a coaxial vacuum window **115**.

The substrate **108** loaded on the substrate holder **107** is arranged to face the electromagnetic wave emitter **103***a* in the slotted antenna **103**.

In the plasma processing system shown in FIG. **9**, the vacuum chamber **102** is evacuated by the evacuating mechanism **101**, discharge gas is introduced into the vacuum chamber **102**, and a predetermined high frequency power is supplied to the slotted antenna **103** by the high frequency power feed system **105**. The introduced discharge gas starts to discharge by the high frequency wave emitted from the electromagnetic wave emitter **103***a* of the slotted antenna **103** and generates plasma in the space in front of the substrate **108** in the vacuum chamber **102**. The surface of the substrate **108** is processed by the physical or chemical action of the generated plasma. For example, if gas having an etching action is introduced as the discharge gas, the surface of the substrate **108** is etched.

Note that in the above-mentioned related art, an industrial frequency of 2.45 GHz is used as the frequency of the high frequency power. Further, the flux density of the magnetic field generated near the antenna by the magnetic circuit, corresponding to the high frequency, is set to be larger than about 875 Gauss so that the frequency of the electron cyclotron becomes equal to 2.45 GHz.

In the field of art of general antennas for transmitting an electromagnetic wave of the microwave to the millimeter wave band, conventionally, the folded waveguide proposed In Japanese Unexamined Patent Publication (Kokai) No. 9-199901 is known. This folded waveguide was proposed to solve the problem of the conventional folded waveguide shown in FIG. 14 of Japanese Unexamined Patent Publication (Kokai) No. 9-199901, that is, the need for formation of reflection surfaces of 45 degrees cuts at the top and bottom of the folded ends and the attachment of adjustment screws for canceling out reflection waves at the reflection surfaces and the resultant complexity of the configuration, the requirement for high dimensional precision, the high cost and inability of mass production, the narrow band of the frequency characteristics, and the troublesome adjustment work. Therefore, the folded waveguide proposed in Japanese Unexamined Patent Publication (Kokai) No. 9-199901 is characterized, as defined for example in claim **1** and claim **2**, by setting an "h" satisfying predetermined conditions in the dimensions a×h (shown in FIG. **1**) of the opening window of the 180 degrees folded portion.

In general the substrates processed by plasma processing systems have become larger in size in recent years. In the process of production of an LSI by processing of a silicon substrate, it is necessary to fabricate a large number of devices from a single substrate, so the size of substrates have become larger. Therefore, the above-mentioned plasma processing systems have been required to be increased in the power of the high frequency wave supplied in order to make the area of the plasma generation region (area of plane parallel to the substrate) larger and to make the plasma density higher for increasing the processing rate.

The antenna device **104** comprised of the above slotted antenna **103** is predicated on the processing of a substrate of a diameter of about 200 mm using plasma of a density of 10^{11} cm^{-3} or so generated by the supply of a high frequency power of about 1 kW. Therefore, it is not possible to supply a large power high frequency wave outside of this assumption and therefore not possible to generate high density plasma suited to the processing of a large area substrate. The reason why a large power high frequency wave cannot be supplied is that a standing wave is generated due to the mismatch of the impedance at the high frequency wave propagation path formed in the slotted antenna **103** and therefore a locally strong electrical field is generated and causes insulation breakdown. Further, the electrical field

induced in the slotted antenna **103** due to the standing wave becomes large and the surface of the slotted antenna **103** is heated by the Joule effect resulting in a loss of power which in turn obstructs the realization of a higher density plasma. In this slotted antenna, it is generally impossible to avoid mismatch of impedance arising due to the discontinuity in the shape of the high frequency wave propagation path.

Further, according to the technology disclosed in Japanese Unexamined Patent Publication (Kokai) No. 9-199901 explained above, it is made possible to match the impedance without adjustment in the folded waveguide of a low loss transmission line of an electromagnetic wave of the microwave to the millimeter wave band and thereby eliminate the reflection wave and thus eliminate the standing wave. This technology, however, is limited to a folded waveguide comprised of the wide area surface of a rectangular waveguide folded substantially 180 degrees. When the width of the wide area surface is made "a" and the width of the narrow wall surface is "b", these dimensions "a" and "b" may be used to give conditions for eliminating the standing wave. Therefore, this technology mainly relates to the structure of the folded portion of a rectangular waveguide and does not relate to an antenna structure. Further, the above publication alludes to a folded radial waveguide (circular waveguide) in its eighth embodiment (FIG. **12** and paragraph **0049** etc.) and claims **12** and **13** as a modification of a folded waveguide. In this case, the folded radial waveguide uses $2\pi r$ ("r" being the distance from the center of the radial waveguide **61** to the center position of the opening of the folded waveguide **64**) as the value corresponding to the width "a" of the wide area surface. It is possible to realize a plane array antenna using the folded radial waveguide, but this is only a modification of the folded waveguide satisfying the predetermined conditions in the end.

In particular, in an antenna used in the above plasma processing system, since a magnetic circuit is provided for forming a magnetic field of a predetermined distribution in the plasma generation space, in actuality a space for accommodating the magnetic circuit is provided and a disk-shaped conductor having a predetermined thickness is used. When using the antenna comprised of the disk-shaped conductor having the above thickness to supply a high frequency power into the vacuum chamber for the processing of the substrate, it is extremely difficult to have the most suitable impedance matching. For the impedance matching and efficient propagation of a high frequency wave without causing a standing wave, a new concept of antenna design suitable for the type and structure of the antenna is required.

SUMMARY OF THE INVENTION

An object of the present invention is to make improvements to the structure of a plasma generation antenna comprised mainly of a disk-shaped conductor having a predetermined thickness and provided with an electromagnetic emitter, while proposing an innovative antenna design technique, and thereby provide an antenna able to prevent the generation of a standing wave in a high frequency wave propagation path and generate high density plasma by the supply of a large power.

Another object of the present invention is to provide a plasma processing system being able to use the antenna to supply a large power high frequency wave, generating high density plasma by a large power, and processing the surface of a large area at a high rate.

The plasma processing system according to the present invention is configured as follows so as to achieve the above objects.

The plasma processing system of the present invention has, as a presupposition configuration, a vacuum chamber in which plasma is generated in a space at the front of a substrate arranged therein, an antenna for plasma generation provided in the vacuum chamber, and a high frequency power source for supplying high frequency power to the antenna. The antenna supplied with the high frequency power from the high frequency power source emits the high frequency power to cause generation of plasma in the space in the vacuum chamber. The plasma is used to perform predetermined processing of the surface of the substrate. Further, in the plasma processing system, the antenna has a disk-shaped conductor having a predetermined thickness and an electromagnetic emitter facing the substrate. It is connected to the high frequency power source by a coaxial line or cable. The disk-shaped conductor is connected to an inside conductor of the coaxial line at its center point. A waveguide of a coaxial type arranged symmetrically with respect to the center point and provided with a folded portion from the coaxial line to the electromagnetic emitter is provided around the disk-shaped conductor. The folded portion of the waveguide is structured as a short-circuit 3 dB directional coupler for impedance matching.

The above-mentioned plasma processing system has a radial waveguide including the disk-shaped conductor having the predetermined thickness due to housing a magnetic circuit and including the folded portion around it. The high frequency power supplied from the top side of the disk-shaped conductor is propagated to the electromagnetic wave emitter at the bottom side through the radial waveguide and is emitted from the electromagnetic wave emitter to the space inside the vacuum chamber. In the antenna having this structure, the waveguide is given the structure of a short-circuit 3 dB directional coupler. This is used for impedance matching to prevent generation of a standing wave.

Among antennas for supply of the high frequency power used in plasma processing systems, there has never before been an antenna having a disk-shaped conductor having a predetermined thickness which can perform impedance matching. According to the present invention, structure enabling impedance matching is realized by this new antenna design technique.

In the plasma processing system according to the present invention, preferably the structure of a short-circuit 3 dB directional coupler is obtained by forming a step difference at one or both of the top surface and bottom surface of the disk-shaped conductor. The disk-shaped conductor having a three-dimensional shape forms a waveguide with the external chamber. The antenna is provided at, for example, the top of the vacuum chamber used as the processing chamber. The high frequency propagation conditions of the waveguide having the folded portion are changed by the formation of the step difference. The structure of the short-circuit 3 dB directional coupler is realized by providing a step difference meeting predetermined conditions regarding the three-dimensional shape of the disk-shaped conductor. Impedance is matched by the waveguide.

Further, in the above configuration, the structure of a short-circuit 3 dB directional coupler is given by providing a plurality of dielectric materials in the region of the waveguide formed around the disk-shaped conductor divided into for example smaller regions and adjusting the heights or dielectric constants of the dielectric materials to satisfy predetermined conditions.

Further, In the above antenna, the variables (dimensions, dielectric constant, etc. of parts) of any elements in the

plurality of elements comprising that structure of a short-circuit 3 dB directional coupler are determined to give $S_{22}=\Gamma_A{}^*$ (where "*" is a conjugated complex number) in the representation of the scattering matrix with respect to the reflection coefficient Γ_A of the antenna. This condition is one example of the predetermined conditions. There are various elements determining the scattering matrix in the above plurality of elements. Further, similarly, in the antenna, the variables of any elements in the plurality of elements comprising the structure of the short-circuit 3 dB directional coupler are determined to give $S_{22}=0$ in the representation of the scattering matrix. This condition is another example of the predetermined conditions and is a basic condition with high practicality.

The plasma processing system according to the present invention is preferably provided with a magnetic circuit for generating a magnetic field in the space inside the disk-shaped conductor. By providing the magnetic circuit, the disk-shaped conductor is given a predetermined thickness. Since the disk-shaped conductor has the predetermined thickness, a new unique technique for antenna design or impedance matching is provided.

In the above configuration, the flux density of the magnetic field generated by the magnetic circuit in the region in proximity to the disk-shaped conductor In the space of the vacuum chamber is set so that the electron cyclotron frequency corresponding to the flux density becomes higher than the frequency of the high frequency power.

Further, in the above configuration, the frequency of the high frequency power is 0.5 to 10 GHz.

In the plasma processing system according to the present invention, preferably a coaxial type impedance matching mechanism is provided at the coaxial line connected to the antenna.

Note that in the above explanation, the explanation was made focusing on a plasma processing system provided with the new high frequency feed antenna, but the antenna itself is also highly valuable technically.

The present invention exhibits the following effects. It provides the plasma processing system supplying a high frequency power into the vacuum chamber to cause discharge and generate plasma and thereby process the surface of a substrate, when the disk-shaped conductor supplying high frequency power has the predetermined thickness, the waveguide surrounding the disk-shaped conductor is given the structure of a short-circuit 3 dB directional coupler. Thereby the generation of a standing wave can be prevented, the high frequency power can be transmitted efficiently, and the efficiency of plasma generation can be improved. Therefore, a large power high frequency wave can be supplied, a high density plasma can be generated, and the surface of a substrate of a diameter more than 300 mm can be processed. Further, according to the present invention, the effect is more remarkable when using discharge resulting from a high frequency power with a frequency in the range of 0.5 to 10 GHz to generate plasma with a good uniformity over a large area. It is possible to improve the practicality of the plasma processing system when processing a large area substrate by high frequency discharge.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other objects and features of the present invention will become clearer from the following description of the preferred embodiments given with reference to the attached drawings, wherein:

FIG. 1 is a longitudinal sectional view of a plasma processing system according to a first embodiment of the present invention:

FIG. 2 is a longitudinal sectional view of the basic structure for supplementing the explanation of the structure of a plasma generation antenna of the first embodiment;

FIG. 3 is a view for explaining the action of the short-circuit 3 dB directional coupler;

FIG. 4 is a longitudinal sectional view of the practical structure for supplementing the explanation of the structure of the plasma generation antenna of the first embodiment;

FIG. 5 is a view of the appearance of a disk-shaped conductor plate of the plasma processing antenna of the first embodiment:

FIG. 6 is a view representing a scattering matrix when viewing the plasma generation antenna as a single power feed system;

FIG. 7 is a longitudinal sectional view of key parts of a plasma generation antenna designed applying this antenna design technique in the first embodiment of the present invention;

FIG. 8 is a longitudinal sectional view of a plasma generation apparatus according to a second embodiment of the present invention; and

FIG. 9 is a longitudinal sectional view schematically showing a plasma processing system of the related art.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Next, preferred embodiments of the present invention will be explained with reference to the attached drawings.

The plasma processing system according to the present invention is in general used for a dry etching system, plasma CVD system, etc. In the following explanation of the embodiments, a dry etching process for fabrication of an LSI is envisioned. The present invention aims at the improvement of the plasma generation mechanism including an antenna. Its applications are not however limited to a dry etching process.

FIG. 1 shows a plasma processing system provided with an antenna as a characteristic part of the present invention. Reference numeral **10** is a plasma generation antenna. In the plasma processing system according to the present invention, the characteristic part lies in the improved structure of the antenna **10**. Therefore, according to this embodiment, the explanation will be made of mainly the structure and action of the antenna **10** referring to the drawings, The overall structure of the plasma processing system is drawn schematically.

The antenna **10** is provided at the top side of a vacuum chamber **12** having a space **11** for generation of plasma inside it. At the bottom part of the inside of the vacuum chamber **12** is provided a substrate holder **13** arranged so as to face the antenna **10**. On the top surface of the substrate holder **13** is loaded a substrate **14** to be processed. The substrate **14** is for example a large sized substrate with a large area having a diameter of 300 mm. The substrate **14** is held horizontally in the figure. The processed surface of the substrate **14** is brought close to the space. The space **11** between the antenna **10** and the substrate holder **13** is a region of generation of plasma. The top surface of the substrate **14** faces the antenna **10** across this space **11**.

In the plasma processing system according to the present embodiment, a gas introduction pipe **15** is provided at a cylindrically shaped surrounding wall of the vacuum chamber **12**. The gas introduction pipe **15** is connected to a discharge gas introduction mechanism **16** through a valve etc. The discharge gas is introduced into the space **11** in the

vacuum chamber **12** through the gas introduction pipe **15**. Under the substrate holder **13** arranged at the bottom of the vacuum chamber **12** is formed an evacuation port **17**. The evacuation port **17** is connected to an evacuating mechanism **18**. The inside of the vacuum chamber **12** is held at a required reduced pressure state by the evacuating mechanism **18**. When electrical power is supplied to the discharge gas of the vacuum chamber **12** in this state, discharge is started and plasma is generated. The antenna **10** is provided at its approximate center position with a disk-shaped conductor plate **19** in a horizontal state in the figure. The power for generation of the plasma is supplied as high frequency power from an electromagnetic wave emitter **20** provided at the bottom surface of the disk-shaped conductor plate **19**. The high frequency power Is supplied from a high frequency power feed system **30** to the disk-shaped conductor plate **19** of the antenna **10**. The disk-shaped conductor plate **19** houses a magnetic circuit near the electromagnetic wave emitter **20**, so has a predetermined thickness. Therefore, the disk-shaped conductor plate **19** is actually formed as a disk-shaped conductor having an inside volume. The thickness of the disk-shaped conductor plate **19** is determined in accordance with the magnitude etc. of the magnetic circuit housed.

In the antenna **10**, the above-mentioned disk-shaped conductor plate **19** is attached at a location outside the opening **12*b*** of the ceiling **12*a*** of the discharge vacuum chamber **12**, so as to plug the same, through a ring **21** made of a dielectric functioning also to seal the vacuum. At the bottom surface of the disk-shaped conductor plate **19**, the part through the opening **12*b*** facing onto the space **11** inside the vacuum chamber **12** forms the above-mentioned electromagnetic wave emitter **204** Also, a thin dielectric plate **22** is attached to the bottom surface of the disk-shaped conductor plate **19**. Further, at the surrounding regions at the upper side, side directions, and lower side of the disk-shaped conductor plate **19** is provided a portion **24** forming a high frequency propagation path, that is, a waveguide **24**. The waveguide **24** is formed as a coaxial high frequency wave propagation path around the disk-shaped conductor plate **19** between the conductor plate **19** and an outside vessel and has a folded portion. Further, around the upper peripheral edge of the disk-shaped conductor plate **19** is provided a ring **23** made of a dielectric in the waveguide **24**. The outer shape of the peripheral edge of the disk-shaped conductor plate **19** forming the waveguide **24** at its inside portion or the structure of the waveguide **24** formed using a dielectric material such as the dielectric rings **21** and **23** and the method of design of the same are the most important points in the present invention.

Further, the above high frequency power feed system **30** is comprised of a high frequency power source **31**, a stub tuner **32**, a coaxial waveguide converter **33**, and a coaxial line **34**. The stub tuner **32** is comprised of three coaxial tuners and is arranged in a waveguide. Further, the coaxial line **34** is comprised of an inner conductor **34*a*** and a tubular outer conductor **34*b***. The inner conductor **34*a*** of the coaxial line **34** is connected to the center of the top surface of the disk-shaped conductor plate **19**, while the bottom end of the outer conductor **34*b*** of the coaxial line **34** is connected to the outside portion of the waveguide **24**. The bottom end of the coaxial line **34** is connected to the top side of the waveguide **24**. Further, the folded portion of the waveguide **24** is formed as a portion extending from the bottom end of the coaxial line **34** to the electromagnetic wave emitter **20** at the bottom side of the disk-shaped conductor plate **19**.

The disk-shaped conductor plate **19** houses a magnetic circuit, or is provided additionally with the magnetic circuit, or assembled with the magnetic circuit for the purpose of improving the efficiency of plasma generation as explained above. The configuration of the magnetic circuit itself, however, is not the gist of the present invention, so in FIG. 1, the illustration is omitted for simplification. As explained above, however, the disk-shaped conductor plate **19** provided with the magnetic circuit is shown by hatching in FIG. 1 to show that it has a predetermined thickness.

The feature of the present invention lies in the structure and action of the plasma generation antenna **10** as explained above. The antenna **10** is provided at the top of the vacuum chamber **12** for discharge processing and is used for the purpose of emitting high frequency power to the inside space of the vacuum chamber **12**. Here, in the explanation of the embodiment, the structure and action of the antenna **10** are the main themes. In the design of the plasma generation antenna **10** constituting the major part of the present invention, the setting of the oscillation frequency of the high frequency power source **31** in the high frequency power feed system **30** is an important requirement. In the present embodiment, in the same way as the document cited above, a high frequency power source able to generate a microwave of 2.45 GHz is used. The output power of the high frequency power source **31** is for example about 2000W.

Next, the structure and action of the antenna **10** will be explained in detail with reference to FIG. **2** to FIG. **6**. FIG. **2** shows schematically the basic structure of the antenna **10**, FIG. **3** illustrates the concept of operation of a short-circuit 3 dB directional coupler by, for example, an example of the structure of a rectangular waveguide, FIG. **4** schematically shows the antenna **10** according to the present invention having the function of impedance matching, FIG. **5** shows a perspective view of the appearance of only the disk-shaped conductor plate, and FIG. **6** shows a representation of a scattering matrix (S matrix) when viewing the antenna **10** as a single power feed system.

In FIG. **2**, the high frequency power introduced through the high frequency power feed system **30** is guided by the coaxial line **34**, passes through the waveguide **24** of the coaxial transmission line formed around the disk-shaped conductor plate **19** of the antenna **10**, and is emitted from the rear electromagnetic wave emitter **20** to the space **11** inside the vacuum chamber **12**. In this figure, the disk-shaped conductor plate of the antenna **10** is the portion shown by reference numeral **19A**. It is shown by a shape different from the above-mentioned conductor plate **19**. That is, the conductor plate **19A** does not actually have the above predetermined thickness and is drawn schematically as a disk-shaped substantially flat plate. Further, in FIG. **2**, the electromagnetic wave emitter **20** designates the opening in the bottom wall. The above high frequency power is the energy for causing discharge of the discharge gas supplied to the space **11** to generate the plasma. In the antenna **10**, as shown by the arrow **41** (meaning an energy flow), the high frequency power is supplied to the electromagnetic wave emitter **20** around the peripheral edge **19A-1** of the disk-shaped conductor plate **19A**. In this configuration, for the efficient propagation of the high frequency power as shown by the energy flow **41**, in the present embodiment, the waveguide **24** of the surrounding region of the disk-shaped conductor plate **19A** is given the structure of a short-circuit 3 dB directional coupler, the special property (action) of the short-circuit 3 dB directional coupler is utilized for impedance matching, and the efficiency of propagation is improved, The present embodiment indicates as its features the method of design of the antenna for giving the structure of a short-circuit 3 dB directional coupler by the waveguide

24 of the antenna 10 and the antenna 10 having the structure. The properties of the short-circuit 3 dB directional coupler will be explained in detail below.

Note that in FIG. 2, the waveguide 24 of the portion of propagation of the high frequency power is divided for convenience into three regions (A), (B) and (C). That is, the waveguide 24 for propagation of the high frequency power around the disk-shaped conductor plate 19A is provided with dielectric materials shown as the three regions (A), (B) and (C). In this example, the structure of the short-circuit 3 dB directional coupler is given as explained later using dielectric materials.

Next, an explanation will be given of the special properties of the short-circuit 3 dB directional coupler using (1) to (4) of FIG. 3. In FIG. 3, the short-circuit 3 dB directional coupler is represented by the block circuit 42 provided with the two left ports 42*a* and 42*b* and the two right ports 42*c* and 42*d*. The top left of the block circuit 42 having the action of the short-circuit 3 dB directional coupler forms an incident end. In the short-circuit 3 dB directional coupler 42, the left ports 42*a* and 42*b* are open, while the right ports 42*c* and 42*d* are short-circuited and form a short-circuited end 42A.

(1) in FIG. 3 is a view of the case where an electromagnetic wave of a unit amplitude is incident to the top right port 42*a* of the short-circuit 3 dB directional coupler. The incident wave is divided by the action of the short-circuit 3 dB directional coupler 42 into two waves of amplitudes of $1/\sqrt{2}$ which appear at the short-circuited end 42A. At this time, due to the general properties of the coupler, the amplitude at the top right port 42*c* becomes $1/\sqrt{2}$, the phase at the bottom right port 42*d* differs by 90 degrees, and therefore the conjugated amplitude becomes $j(1/\sqrt{2})$.

In the short-circuit 3 dB directional coupler 42, when the incident wave enters the, port 42*a* as explained above, reflection occurs at the short-circuited end 42A. As shown in (2) and (3) of FIG. 3. the reflection wave again passes through the short-circuit 3 dB directional coupler 42. (2) of FIG. 3 is a view of the case of reflection of the electromagnetic wave of the amplitude $1/\sqrt{2}$ of the port 42*c*. As a result, this becomes the electromagnetic waves of the conjugated amplitudes ½ and j(½) and appears at the two ports 42*a* and 42*b*. On the other hand, (3) of FIG. 3 is a view of the case of reflection of the electromagnetic wave of the conjugated amplitude $j(1/\sqrt{2})$ of the port 42*d*. Electromagnetic waves of the conjugated amplitudes −½ and j(½) appear at the ports 42*a* and 42*b*. Since the overall phenomenon is based on the superposition of (2) and (3) of FIG. 3, in the end, the electromagnetic wave passing through the short-circuit 3 dB directional coupler 42 and reflected at the short-circuited end 42A appears as the conjugated amplitude j at the bottom left port 42*b* as shown in (4) of FIG. 3. In short, due to the action of the short-circuit 3 dB directional coupler 42, the electromagnetic wave incident from the port 42*a* of the incident end is output as an electromagnetic wave with an unchanging amplitude and a 90 degrees different phase at the left port 42*b*. That is, the electromagnetic wave incident to the port 42*a* is transmitted to the port 42*b* as an electromagnetic wave shifted in phase by exactly 90 degrees without generation of a standing wave.

If configuring the short-circuit 3 dB directional coupler having the above action by a rectangular waveguide, the port 42*a* where the electromagnetic wave is incident becomes the incident side waveguide, while the port 42*b* where the electromagnetic wave is output becomes the emission side waveguide. The portion of the waveguide from the incident side waveguide to the emission side waveguide is formed as a folded portion by the provision of the short-circuit use metal plate portion. If configuring the short-circuit 3 dB directional coupler having a folded portion using the structure of the rectangular waveguide in this way, the high frequency power entering from the incident side waveguide is output from the emission side waveguide without the generation of a standing wave.

The discussion of the short-circuit 3 dB directional coupler relating to the above rectangular waveguide can be expanded and applied to the antenna 10 comprised of the disk-shaped conductor plate 19A and waveguide 24 formed around it, shown in FIG. 2, that is, the antenna 10 having the radial waveguide including the folded portion. The basic operating principle of the short-circuit 3 dB directional coupler 42 relating to the example of the structure using the rectangular waveguide is the same in the antenna 10 of the shape shown in the present embodiment. That is, In the antenna 10, if the generation of the standing wave is eliminated by structural provision (structural realization) of the short-circuit 3 dB directional coupler at the waveguide 24 at the region surrounding the disk-shaped conductor plate 19A, the power of the high frequency wave (microwave) introduced to the incident portion of the top side of the disk-shaped conductor plate 19A is efficiently propagated without generation of loss as shown by the energy flow 41 and is emitted from the electromagnetic wave emitter 20 of the lower, side of the disk-shaped conductor plate 19A In the example of the antenna 10 shown in FIG. 2, the short-circuit 3 dB directional coupler is realized by arranging dielectric materials of the regions (A) to (C) so as to satisfy predetermined conditions at the waveguide 24 formed around the flat disk-shaped conductor plate 19A. Here, the "predetermined conditions" means finding a single scattering matrix S as an overall structure for the waveguide 24 of the antenna 10 and changing the dielectric constants etc. of the dielectric materials of the regions (A) to (C) to make the reflection coefficient S_{22} of the scattering matrix 0. In other words, if the dielectric constants etc. of the dielectric materials are determined so that the reflection coefficient S_{22} of the scattering matrix becomes 0, the short-circuit 3 dB directional coupler is provided at the waveguide 24 by the structure of the dielectric materials of the regions (A) to (C) having those dielectric constants.

Further, since there are various demands in practice on the structure of the plasma/generation antenna 10, it is not possible to employ the above ideal structure as it is. In practice, since a magnetic circuit using permanent magnets is provided close to the electromagnetic wave emitter 20, when the magnetic circuit is contained in the disk-shaped conductor plate 19, the disk-shaped conductor plate 19 is required to have a predetermined thickness in accordance with the housed magnetic circuit as shown in FIG. 1.

Further, similarly, as shown in FIG. 1, the distance between the electromagnetic wave emitter 20 and the disk-shaped conductor plate 19 is in many cases made several mm. Sometimes it has to be made extremely small compared with the distance or clearance at the top side of the disk-shaped conductor plate 19. If such a shape is employed, however, the impedances at the top and bottom surfaces of the disk-shaped conductor plate 19 will become considerably different and therefore microwave reflection will occur.

Therefore, relating to the outside shape of the disk-shaped conductor plate, unlike the flat disk-shaped conductor plate 19A shown in FIG. 2, tie structure shown in FIG. 4 is employed. The disk-shaped conductor plate shown in FIG. 4 is formed to have an impedance matching function so as not to cause microwave reflection by giving a predetermined

thickness and making modifications in the outside shape. The outer shape of the disk-shaped conductor plate shown in FIG. 4 is the same as the outer shape of the disk-shaped conductor plate 19 shown in FIG. 1. Therefore, the reference numeral 19 is assigned to the disk-shaped conductor plate shown in FIG. 4 as well. According to this structure, as shown in FIG. 4 and FIG. 5, step differences 19*a* and 19*b* are formed at the peripheral edges of the top and bottom surfaces of the disk-shaped conductor plate 19 and the dimensions are suitably designed in accordance with the method of design of the antenna explained below for impedance matching. In this example, by providing step differences 19*a* and 19*b* at the top and bottom surfaces of the disk-shaped conductor plate 19 under predetermined conditions, propagation characteristics of the high frequency power the same as the short-circuit 3 dB directional coupler 42 whose operating principle was explained in FIG. 3 are realized. That is, the structure of a short-circuit 3 dB directional coupler is realized by providing the step differences 19*a* and 19*b* meeting predetermined conditions at the top and bottom surfaces of the disk-shaped conductor plate 19 of the antenna 10. Here, the "predetermined conditions" means finding one scattering matrix S as an overall structure for the waveguide 24 of the antenna 10 and changing the heights and other dimensions of the step differences 19*a* and 19*b* to make the reflection coefficient S_{22} of the scattering matrix 0. In other words, if the heights etc. of the step differences are determined so that the reflection coefficient S_{22} of the scattering matrix becomes 0, the short-circuit 3 dB directional coupler is provided at the waveguide 24 by the structure of the step differences. By providing the step differences 19*a* and 19*b* of the predetermined conditions at the top and bottom surfaces of the disk-shaped conductor plate 19 in this way, the impedances are matched, the generation of microwave reflection is prevented, the microwave is efficiently transmitted, and a microwave can be efficiently emitted from the electromagnetic wave emitter 20.

Further, to practically provide the antenna 10 with the disk-shaped conductor plate having the outer shape as shown in FIG. 4 and FIG. 5, it is necessary to change the outer shape of the disk-shaped conductor plate 19 and to consider the selection of the dielectric materials to be arranged around the disk-shaped conductor plate, design of the vacuum sealing, etc. That is, to specifically design the antenna 10, it is necessary to design the microwave propagation path by changing the outer shape of the disk-shaped conductor plate 19 and select the surrounding dielectric materials, design the vacuum sealing, etc. Therefore, the dielectric rings 21 and 23 are arranged around the disk-shaped conductor plate 19 as explained in FIG. 1. The dielectric rings 21 and 23 form the waveguide 24 and serve also as vacuum seals. When designing the antenna 10 of the configuration shown in FIG. 1, the antenna is designed by changing the outer shape by the step differences of the disk-shaped conductor plate 19, selecting the dielectric materials (21, 22, 23) provided at the waveguide 24, etc. and finding one scattering matrix S as the overall structure and changing a certain portion of the structure to give a reflection coefficient S_{22} of the scattering matrix of 0 and thereby realize the structure of the short-circuit 3 cm directional coupler at the waveguide 24 of the antenna.

Next, the method of antenna design relating to the antenna 10 will be described in detail. Here, the process of calculation for realizing a waveguide for propagation of a microwave without reflection is shown for a basic structure obtained by using a material usable for a plasma surface processing system and giving consideration to the mechanical strength.

FIG. 6 is a view for explaining the basic operation of the plasma generation antenna 10. It shows one scattering matrix (S matrix) obtained by viewing the antenna 1 as a single power feed system. The scattering matrix S is comprised of the reflection coefficients S_{11} and S_{22} and the transmission coefficients S_{12} and S_{21}. In FIG. 6, when the reflection coefficient of the antenna 10 is Γ_A and the scattering matrix of the antenna 10 when viewed as a power feed system is made the following equation (1), the reflection coefficient at the feeding point of the antenna 10 is expressed by the following equation (2):

$$[S] = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \tag{1}$$

$$\Gamma_F = e^{j2\phi}\Gamma_A - \frac{S'_{22}}{1 - S_{22}\Gamma_A} \tag{2}$$

Note that in equation (2), the symbol * expresses a conjugated complex number and $\phi=\arg(S_{11})$ . . . (3). For simplification, in the representation of the scattering matrix of FIG. 6. the reference plane is moved to the position T—T where $\phi=0$.

Here, when the reflection coefficient Γ_A of the antenna 10 is known, if designing the power feed system so that $S_{22}=\Gamma_A{}^*$ . . . (4), $\Gamma_F=0$ . . . (5) and complete matching becomes possible.

However, the reflection coefficient Γ_A at the antenna 10, that is, the reflection coefficient Γ_A at the electromagnetic wave emitter 20, is generally unknown. The above method of calculation cannot be applied. Therefore, in equation (2), the antenna is designed to satisfy $S_{22}=0$ . . . (6). If $S_{11}=0$, $\Gamma_F=\Gamma_A$ . . . (7) stands and the reflection coefficient of the antenna 10 and the reflection coefficient of the feeding point become equal. That is, if ensuring the condition $S_{22}=0$ be satisfied while changing a certain portion of the structure forming the antenna 10, the state of change gives the structure of the short-circuit 3 dB directional coupler and impedance matching is achieved.

Next, the method of finding the elements of the scattering matrix of equation (1) for the plasma generation antenna 10 shown in FIG. 2 as an example will be shown. To facilitate the analysis at this time, the Inside of the cylinder of the inside diameter R (waveguide 24) is divided into three regions (A), (B) and (C) as shown in FIG. 2. The heights h_1, h_2 and h_3 and the dielectric constants $\epsilon_\gamma^{(1)}$, $\epsilon_\gamma^{(2)}$ and $\epsilon_\gamma^{(3)}$ are respectively assigned to these regions. The excitation is made the TM wave and the electromagnetic field is made uniform in the ϕ direction. At this time, the electrical component E_Z is obtained by solution of the wave equation in the cylindrical coordinate system shown in equation (8), while the magnetic wave component $H\phi$ is found by equation (9).

$$\frac{\partial^2 E_Z}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial E_Z}{\partial \rho} + k^2 E_X = 0 \tag{8}$$

$$H_\phi = -\frac{1}{j\omega\mu}\frac{\partial E_Z}{\partial \rho} \tag{9}$$

The electromagnetic fields in the region (A), region (B) and region (C) are given by the following equations (10) to (16) in this way:

$$E_r^{(1)} = \frac{H_0^{(2)}(k_0^{(1)}\rho)}{H_0^{(2)}(k_0^{(1)}\gamma)} + \sum_{n=0}^{\infty} A_n^{(1)} - \frac{H_0^{(1)}(k_n^{(1)}\rho)}{H_0^{(1)}(k_n^{(1)}\gamma)} \cos\left(\frac{n\pi}{h_1}z\right) \tag{10}$$

$$H_\phi^{(1)} = \frac{jH_1^{(2)}(k_0^{(1)}\rho)}{Z_0^{(1)}H_0^{(2)}(k_0^{(1)}r)} + j\sum_{n=0}^{\infty} \frac{A_n^{(1)}H_1^{(1)}(k_n^{(1)}\rho)}{Z_n^{(1)}H_0^{(1)}(k_n^{(1)}r)} \cos\left(\frac{n\pi}{h_1}z\right) \tag{11}$$

$$E_z^{(2)} = \sum_{n=0}^{\infty} A_n^{(2)} \frac{H_0^{(1)}(k_n^{(2)}\rho)}{H_0^{(1)}(k_n^{(2)}r)} \cos\left[\frac{n\pi}{h_2}(z-(h_3-h_2))\right] \tag{12}$$

$$H_\phi^{(2)} = j\sum_{n=0}^{\infty} \frac{A_n^{(2)}H_1^{(1)}(k_n^{(2)}\rho)}{Z_n^{(2)}H_0^{(1)}(k_n^{(2)}r)} \cos\left[\frac{n\pi}{h_2}(z-(h_3-h_2))\right] \tag{13}$$

$$E_z^{(3)} = \sum_{n=0}^{\infty} A_n^{(3)} \left[\frac{H_0^{(2)}(k_n^{(3)}\rho)}{H_0^{(2)}(k_n^{(3)}R)} - \frac{H_0^{(1)}(k_n^{(3)}\rho)}{H_0^{(1)}(k_n^{(3)}R)}\right] \cos\left(\frac{n\pi}{h_3}z\right) \tag{14}$$

$$H_\phi^{(3)} = j\sum_{n=0}^{\infty} \frac{A_n^{(3)}}{Z_n^{(3)}} \left[\frac{H_1^{(2)}(k_n^{(3)}\rho)}{H_0^{(2)}(k_n^{(3)}R)} - \frac{H_1^{(1)}(k_n^{(3)}\rho)}{H_0^{(1)}(k_n^{(3)}R)}\right] \cos\left(\frac{n\pi}{h_3}z\right) \tag{15}$$

$$k_n^{(i)} = \sqrt{k_n^2\varepsilon_r^{(i)} - \left(\frac{n\pi}{h_i}\right)^2}, \quad Z_n^{(i)} = \frac{k_n^{(i)}}{\omega\varepsilon_0\varepsilon_r^{(i)}}, \ (i = 1, 2, 3) \tag{16}$$

Here, $A_n^{(1)}$ is an unknown coefficient, $k_n^{(1)}$ is a phase constant, $Z_n^{(1)}$ is a characteristic impedance, and n is a mode number. Further, the first terms on the right sides of equations (10) and (11) correspond to incident waves, the second terms on correspond to reflection waves, and equations (12) and (13) correspond to transmission waves. These must satisfy the boundary condition at ρ=γ (following equations (17), (18) and (19)).

$$E_z^{(3)} = \begin{cases} E_z^{(1)}(0 \le z \le h_1) \\ 0(h_1 \le z \le h_3 - h_2) \\ E_z^{(2)}(h_3 - h_2 \le z \le h_3) \end{cases} \tag{17}$$

$$H_\phi^{(1)} = H_\phi^{(3)}(0 \le z \le h_1) \tag{18}$$

$$H_\phi^{(2)} = H_\phi^{(3)}(h_3 - h_2 \le z \le h_3) \tag{19}$$

Here, if equations (10) to (15) are inserted into equations (17) to (19) and the results multiplied with the following equation shown below to integrate them in the range where the boundary conditions stand, equations (20) to (22) are obtained.

$$\cos\left(\frac{m\pi}{h_3}z\right), \cos\left(\frac{m\pi}{hl}z\right), \tag{20}$$

$$\cos\left(\frac{m\pi}{h_2}(z-(h_3-h_2))\right)[h_3 Z_n^{(3)}][S_n](A_n^{(3)}) = h_1 Z_0^{(1)}[\varepsilon_n](\alpha_{m0}^{(1)}) + [\varepsilon_n][\alpha_{mn}^{(1)}][h_1 Z_n^{(1)}](A_n^{(1)}) + [\varepsilon_n][\alpha_{mn}^{(2)}][h_2 Z_n^{(2)}](A_n^{(2)})$$

$$(A_m^{(1)}) = I(\delta_n) + [\varepsilon_n][J_n^{(1)}][\alpha_{mn}^{(1)}]^t[C_n](A_n^{(3)}) \tag{21}$$

$$(A_m^{(2)}) = [\varepsilon_n][J_n^{(2)}][\alpha_{mn}^{(2)}]^t[C_n](A_n^{(3)}) \tag{22}$$

Here, the bracketed terms indicate matrixes, while the parenthesized terms indicate column vectors. A term with a single element number such a $[S_n]$ is a diagonal matrix. Note

that the elements are given by the following equations (23) to (28):

$$\alpha_{mn}^{(1)} = (-1)^n m\pi\frac{h_1}{h_3}\frac{\sin\left(m\pi\frac{h_1}{h_3}\right)}{\left(m\pi\frac{h_2}{h_3}\right)^2 - (n\pi)^2} \tag{23}$$

$$a_{mn}^{(2)} = (-1)^{H_2} m\pi\frac{h_2}{h_3} - \frac{\sin\left(m\pi\frac{h_2}{h_3}\right)}{\left(m\pi\frac{h_2}{h_3}\right)^2 - (n\pi)^2} \tag{24}$$

$$S_n = \frac{H_0^{(2)}(k_n^{(3)}r)}{H_0^{(2)}(k_n^{(3)}R)} - \frac{H_0^{(1)}(k_n^{(3)}r)}{H_0^{(1)}(k_n^{(3)}R)} \tag{25}$$

$$C_n = \frac{H_1^{(2)}(k_n^{(3)}r)}{H_0^{(2)}(k_n^{(3)}R)} - \frac{H_1^{(1)}(k_n^{(3)}r)}{H_0^{(1)}(k_n^{(3)}R)} \tag{26}$$

$$J_n^{(i)} = \frac{H_0^{(1)}(k_n^{(i)}r)}{H_1^{(1)}(k_n^{(i)}r)}, \ (i = 1, 2) \tag{27}$$

$$\varepsilon_n = \begin{cases} 1(n=0) \\ 2(n \ne 0) \end{cases}, \quad \delta_n = \begin{cases} 1(n=0) \\ 0(n \ne 0) \end{cases} \tag{28}$$

Here, I is expressed by the following equation (29):

$$I = \frac{H_1^{(2)}(k_0^{(1)}r)H_0^{(1)}(k_0^{(1)}r)}{H_0^{(2)}(k_0^{(1)}r)H_1^{(1)}(k_0^{(1)}r)} \tag{29}$$

If equations (21) and (22) are inserted into equation (20), the following equation (30) is obtained.

$$\begin{aligned}[[h_3 Z_n^{(3)}][S_n] - [\varepsilon_\pi][\alpha_{mn}^{(1)}][h_1 Z_n^{(1)}][\varepsilon_\pi][J_n^{(1)}][\alpha_{mn}^{(1)}]^t[C_n] - \\ [\varepsilon_\pi][\alpha_{mn}^{(2)}][h_2 Z_n^{(2)}][\varepsilon_n][J_y^{(2)}][\alpha_{mn}^{(2)}]^t[C_n]](A_\pi^{(3)}) \\ = (1 + I)h_1 Z_0^{(1)}[\varepsilon_n](\alpha_{m0}^{(3)})\end{aligned} \tag{30}$$

By solving equation (30) for $A_m^{(3)}$ and inserting the result into equations (21) and (22), $A_m^{(1)}$ and $A_m^{(2)}$ are found. In the end, the elements S_{11}, S_{12} and S_{21} of the scattering matrix are given by the following equations (31) and (32):

$$S_{11} = A_0^{(1)}\sqrt{-\frac{H_1^{(1)}(k_0^{(1)}r)H_0^{(2)}(k_0^{(1)}r)}{H_0^{(1)}(k_0^{(1)}r)H_1^{(2)}(k_0^{(1)}r)}} \tag{31}$$

$$S_{12} = S_{21} = A_0^{(2)}\sqrt{-\frac{h_2 Z_0^{(2)} H_1^{(1)}(k_0^{(2)}r)H_0^{(2)}(k_0^{(1)}r)}{h_1 Z_0^{(1)} H_0^{(1)}(k_0^{(2)}r)H_1^{(2)}(k_0^{(1)}r)}} \tag{32}$$

Using the unitary property, S_{22} is obtained by the following equation (33):

$$S_{22} = -\frac{S_{21}}{S_{21}^*}S_{11}^* \tag{33}$$

By suitably changing a certain portion of the plurality of variables (heights h_1, h_2 and h_3 and dielectric constants $\epsilon_\gamma^{(1)}$, $\epsilon_\gamma^{(2)}$ and $\epsilon_\gamma^{(3)}$) in S_{22} obtained by equation (33), it is possible

to provide the structure of the short-circuit 3 dB directional coupler at the antenna **10**. In this way, it is possible to obtain elements of the scattering matrix relating to the plasma generation antenna **10** shown in FIG. **2** and possible to use the reflection coefficient S_{22} among these to precisely find the dimensions or dielectric constants etc. of the parts of the antenna **10** enabling impedance matching.

It is also possible to use the same method of design as above for analysis to find the elements of the scattering matrix in the design of the antenna **10** having the disk-shaped conductor plate **19** formed with the step differences **19***a* and **19***b* shown in FIGS. **4** and **5**. That is, the antenna is designed by multi variable analysis using as variables the distance between the peripheral edge of the disk-shaped conductor plate and the outer vessel, the heights of the step differences, the distance between the peripheral edge of the disk-shaped conductor plate and the walls of the step differences, and the distance between the bottom surfaces of the step differences and the outer vessel. In this way, it is possible to precisely find the dimensions etc. of the step differences of the antenna **10** able to perform impedance matching using the reflection coefficient S_{22} of the scattering matrix even for the plasma generation antenna **10** shown in FIG. **4** etc.

An example of the folded portion around the peripheral edge of the disk-shaped conductor plate **19** designed in the above way for the plasma generation antenna **10** having the step differences **19***a* and **19***b* shown in FIG. **4** is shown in FIG. **7**. The antenna **10** shown in FIG. **7** is designed so that the reflection coefficient Γ_F at the feeding point of the antenna **10** deemed to be the power feed system matches with the reflection coefficient Γ_A at the electromagnetic wave emitter of the antenna **10**. In FIG. **7** the reference numeral **19** indicates the disk-shaped conductor plate of the antenna **10**, while **24***a* is a conductive outside vessel. The step difference **19***a* is formed on the top sur ace of the disk-shaped conductor plate **19**, while the step difference **19***b* is formed on the bottom surface. The above waveguide **24** is formed between the outside vessel **24***a* and the disk-shaped conductor plate **19** positioned inside it. The dimensions of the parts of the antenna **10** are as follows. The height of the outside vessel **24***a* is 8 cm. The distance between the maximum diameter portion (peripheral edge) positioned at the center of the disk-shaped conductor plate **19** in the thickness direction and the cylindrical side walls of the outside vessel **24***a* is 5 cm. The dimension of width of the step difference **19***a* in the diametrical direction is 3 cm, while the dimension from the surface (bottom surface) **19***a*-**1** in the step difference **19***a* to the upper wall of the outside vessel **24***a* is 2 cm. The dimension of width of the step difference **19***b* in the diametrical direction is 3 cm, while the dimension from the surface (bottom surface) **19***b*-**1** in the step difference **19***b* to the bottom wall of the outside vessel **24***a* is 1.5 cm.

According to the antenna **10** designed so that the reflection coefficient Γ_A and the reflection coefficient Γ_F of the waveguide **24** match as explained above, by inserting three stub tuners into the above coaxial line **34**, it is possible to even more easily match the impedance. Note that at this time, the coaxial waveguide converter **33** must be designed to be able to substantially completely match the impedance at the frequency used, that is 2.4 GHz.

Further, as a result of actual measurement, when it becomes clear that the reflection coefficient Γ_A is large, it is sufficient to insert that value into equation (4) and redesign the plasma generation antenna. By applying this technique to the design of a plasma generation antenna, it is possible to construct a plasma processing system which improves the efficiency of transmission of electromagnetic waves in the antenna power feed system, a problem in the past, and has advantages never seen in the past. These advantages are the following (1) to (3):

(1) A plasma processing system which can emit a large power electromagnetic wave impossible in the past, and can generate higher density plasma than ever before can be provided.

(2) Plasma of the same extent of density as in the past can be generated using a smaller power than in the past, so the plasma processing system can be given a smaller power source and be made smaller in energy consumption. Further, the rate of increase of the power for dealing with the increasing size of plasma generation areas accompanying the processing of large area substrates can be suppressed.

(3) The method of design of an antenna according to the present embodiment defines the structure of the electromagnetic wave transmission path. Optimal design assuming any shape or material for the desired process becomes possible.

Note that the design shown in the first embodiment is one example of the result of calculations. It is of course possible to calculate other efficient structures using similar calculations. Due to the above reasons, according to the plasma generation antenna **10** according to the above embodiment, it is possible to minimize the power loss in the inside of the plasma generation antenna and possible to realize a plasma generation system of a higher efficiency than ever before.

Next, the routine and features when processing the surface of a substrate **14** by using the plasma processing system according to the first embodiment will be explained in brief. The surface processing is for example a dry etching process of a silicon oxide film on a silicon wafer.

In the plasma processing system according to the first embodiment, discharge gas is supplied from the discharge gas introduction mechanism **16** through the gas introduction pipe **15** to the vacuum chamber **12**. As the discharge gas used in the dry etching process of a silicon oxide film, generally use is made of a mixed gas comprised mainly of a chlorofluorocarbon gas plus argon, oxygen, hydrogen, etc. On the other hand, the evacuating mechanism **18** provided at the vacuum chamber **12** is provided with a hydraulic rotary pump or turbo molecular pump or other vacuum pump. The inside of the vacuum chamber **12** is evacuated through the evacuation port **17** until reaching for example a pressure of about 10^{-4} Pa. Note that the vacuum chamber **12** is also provided with a gate valve for loading and unloading the substrates **14** and a transport system for loading and unloading the substrates **14** through the gate valve, but illustration of these is omitted in FIG. **1**.

Next, an explanation will be given of the operation of the above plasma processing system. First, the not shown transport system is used to load the substrate **14** into the vacuum chamber **12** and place it on the substrate holder **13**. The evacuating mechanism **18** is then operated to evacuate the inside of the vacuum chamber **12** to about 10^{-4} Pa, then the discharge gas introduction mechanism **16** introduces the discharge gas into the vacuum chamber **12**. The pressure of the gas inside the vacuum chamber **12** is determined by the flow rate of introduction of the gas and the evacuation rate of the evacuating mechanism **18**. The typical gas pressure in the plasma processing system of the present embodiment is about 1 Pa. To maintain the predetermined discharge pressure at the predetermined gas flow rate the general practice has been to provide the evacuating mechanism **18** with a mechanism for controlling the evacuation rate.

Next, the high frequency power feed system **30** operates to supply high frequency power to the vacuum chamber **12**. That is, the high frequency power generated from the high frequency power resource **31** is guided by the waveguide to the stub tuner **32** where the impedance is matched, then is converted by the coaxial waveguide converter **33** and is supplied through the coaxial line **34** to the plasma generation antenna **10**. The high frequency power supplied to the antenna **10** is emitted from the electromagnetic wave emitter **20** to the space **11** in accordance with the action of the antenna **10** to electrically dissociate the discharge gas in the space **11** and cause discharge. Plasma is generated in the space **11** inside of the vacuum chamber **12** by this discharge. This plasma is used for the predetermined processing of the surface of the substrate **14** on the substrate holder **13**.

In the above plasma processing system, the features of the antenna **10** were used to enable generation of high density plasma, which had been impossible in the past. The uniformity of the plasma is within ±3% in the case of a diameter in the range of 300 mm. This value is sufficient for a plasma processing system using current silicon substrates. Further. from the features of the plasma generation antenna **10**, it becomes easy to generate uniform plasma by a larger area. The antenna can therefore be applied to a system for processing of a large-sized substrate of a diameter of 400 mm or a diameter of 450 mm in the future.

FIG. **8** shows a second embodiment of the present invention and is similar to FIG. **1**. In FIG. **8**, the same reference numerals are assigned to elements substantially the same as the elements explained in FIG. **1** and explanations are omitted. In particular, the structure providing the short-circuit 3 dB directional coupler of the plasma generation antenna **10** in this embodiment is substantially the same as that explained in the first embodiment. In the present embodiment, matching even closer to the ideal can be realized by providing a coaxial stub tuner **51** in the coaxial line **34**.

In the antenna **10** optimally designed in accordance with the first embodiment, the design is based on the presumption that the reflection coefficient of the electromagnetic wave emitter is sufficiently small or known. The impedance of the plasma generated however changes somewhat according to the input power, gas pressure, etc., so the reflection coefficient also changes somewhat in accordance with the impedance of the plasma. The plasma source shown in the first embodiment is an ECR plasma source provided with a magnetic circuit at the disk-shaped conductor plate **19** of the antenna **10** and using the magnetic field as explained above. In this case, the change of the impedance is small, but when applying the present invention to a plasma source of the type generating plasma without using the magnetic field, the change of the reflection coefficient sometimes becomes a problem. Therefore, to eliminate the reflection wave caused in the waveguide in the antenna **10** due to the change of the impedance of the plasma, the coaxial stub tuner **51** is added to the coaxial line **34** for supplying high frequency power to the antenna **10**. By adding this configuration, it is possible to cancel out the reflection wave generated due to the change of the reflection coefficient by the standing wave generated by the coaxial stub tuner **51** and realize a completely matched state without relying on a change of the process conditions.

The structure of the plasma generation antenna **10** used for the plasma processing system according to the present invention is not limited to the above embodiment. If the conditions sought for the above short-circuit 3 dB directional coupler are satisfied, it is possible to freely change the shape and material of the dielectric rings and blocks, the outer diameter and thickness of the disk-shaped conductor plate, the shapes of the step differences, and other dimensions, since the application of the plasma generation antenna designed by the system of the present invention is a plasma source for a semiconductor manufacturing system, due to the wavelength of the electromagnetic wave, it is preferable to set the frequency used to a range of 0.5 to 10 GHz. Further, by designing the antenna predicated on use at a frequency of 0.915 GHz or 2.45 GHz for which use is permitted as an industrial frequency, it is possible to realize a more practical plasma generation antenna.

In the above embodiments, the example was shown of the use of the plasma processing system according to the present invention to dry etching, but the object of the present invention lies in generating plasma efficiently and with a good uniformity using a high frequency wave as explained above. Therefore, even when applying the invention to a plasma processing system meant for all types of surface processing using plasma such as plasma CVD, plasma oxidation, and plasma polymerization, the same effect as explained in the embodiments can be obtained. While the invention has been described by reference to specific embodiments chosen for purposes of illustration, it should be apparent that numerous modifications could be made thereto by those skilled in the art without departing from the basic concept and scope of the invention.

What is claimed is:

1. A plasma processing system comprising:

a vacuum chamber in which plasma is generated in a space at the front of a substrate loaded inside,

an antenna for plasma generation provided in said vacuum chamber,

a high frequency power source for supplying high frequency power to said antenna,

wherein said antenna supplied with the high frequency power from said high frequency power source emitting the high frequency power to cause generation of plasma in the space in said vacuum chamber and the plasma being used to perform predetermined processing of the surface of said substrate, and further wherein,

said antenna having a disk-shaped conductor having a predetermined thickness and an electromagnetic wave emitter facing said substrate and being connected to said high frequency power source by a coaxial line,

said disk-shaped conductor being connected to an inside conductor of said coaxial line at its center point,

a waveguide of a coaxial type arranged symmetrically with respect to the center point and provided with a folded portion from said coaxial line to said electromagnetic wave emitter being provided around said disk-shaped conductor, and

said folded portion of said waveguide having structure as a short-circuit 3 dB directional coupler having an impedance matching action.

2. A plasma processing system as set forth in claim **1**, wherein the structure as said short-circuit 3 dB directional coupler is produced by forming a step difference at one or both of the top surface and bottom surface of said disk-shaped conductor.

3. A plasma processing system as set forth in claim **1**, wherein the structure as said short-circuit 3 dB directional coupler is produced by providing dielectric materials at the waveguide around said disk-shaped conductor.

4. A plasma processing system as set forth in claim **1**, wherein in said antenna, the variables of any elements in the plurality of elements comprising the structure as said short-circuit 3 dB directional coupler are determined to give $S_{22}=\Gamma_A{}^*$ (where "*" is a conjugated complex number) in a representation of a scattering matrix with respect to a reflection coefficient Γ_A of said antenna.

5. A plasma processing system as set forth in claim **1**, wherein in said antenna, the variables of any elements in the plurality of elements comprising the structure as said short-circuit 3 dB directional coupler are determined to give $S_{22}=0$ in a representation of a scattering matrix.

6. A plasma processing system as set forth in claim **1**, wherein a magnetic circuit for generating a magnetic field in the space is provided at said disk-shaped conductor.

7. A plasma processing system as set forth in claim **6**, wherein the flux density of the magnetic field generated by said magnetic circuit in a region in proximity to said disk-shaped conductor in the space is set so that the electron cyclotron frequency corresponding to the flux density becomes larger than the frequency of the high frequency power.

8. A plasma processing system as set forth in claim **1**, wherein the frequency of the high frequency power is 0.5 to 10 GHz.

9. A plasma processing system as set forth in claim **1**, wherein a coaxial type impedance matching mechanism is provided at said coaxial line.

* * * * *

US006357385B1

(12) **United States Patent**
Ohmi et al.

(10) **Patent No.: US 6,357,385 B1**
(45) **Date of Patent: Mar. 19, 2002**

(54) **PLASMA DEVICE**

(75) Inventors: **Tadahiro Ohmi**, 1-17-301, Komegabukuro 2-chome, Aoba-ku, Sendai, Miyagi-ken 980; **Takahisa Nitta**, Tokyo; **Masaki Hirayama**, Miyagi-ken; **Haruyuki Takano**, Miyagi-ken; **Ryu Kaiwara**, Miyagi-ken, all of (JP)

(73) Assignee: **Tadahiro Ohmi**, Miyagi-ken (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/355,229**

(22) PCT Filed: **Jan. 29, 1998**

(86) PCT No.: **PCT/JP98/00364**

§ 371 Date: **Oct. 5, 1998**

§ 102(e) Date: **Oct. 5, 1998**

(87) PCT Pub. No.: **WO98/33362**

PCT Pub. Date: **Jul. 30, 1998**

(30) **Foreign Application Priority Data**

Jan. 29, 1997	(JP)	9/15790
May 23, 1997	(JP)	9/133422
Sep. 25, 1997	(JP)	9/278062

(51) **Int. Cl.**^{7} **C23C 16/00**

(52) **U.S. Cl.** .... **118/723 AN**; 156/345; 118/723 MW

(58) **Field of Search** .... 118/723 MW, 118/723 MR, 723 ME, 723 MA, 723 I, 723 IR, 723 AN; 156/345

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,525,159 A * 6/1996 Hama et al. 118/723

FOREIGN PATENT DOCUMENTS

JP	61-265820 A	11/1986	H01L/21/302
JP	63-50477 A	3/1988	C23C/16/50
JP	1-298183 A	12/1989	C23F/4/00
JP	3-55832 A	3/1991	H01L/21/302
JP	4-221824 A	8/1992	H01L/21/302
JP	5-62913 A	3/1993	H01L/21/205
JP	6-224183 A	8/1994	H01L/21/31
JP	07307326 A	11/1995	H01L/21/3065
JP	0804917 A	2/1996	H01L/21/3065
JP	08111297 A	4/1996	H05H/1/46
JP	09027397 A	1/1997	H05H/1/46

OTHER PUBLICATIONS

International Preliminary Examination Report, International Application No. PCT/JP98/00364, Filing Date Jan. 29, 1998, Priority Date Jan. 29, 1997.

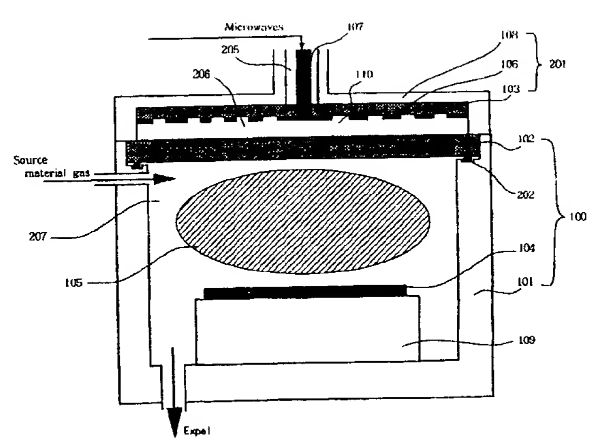
* cited by examiner

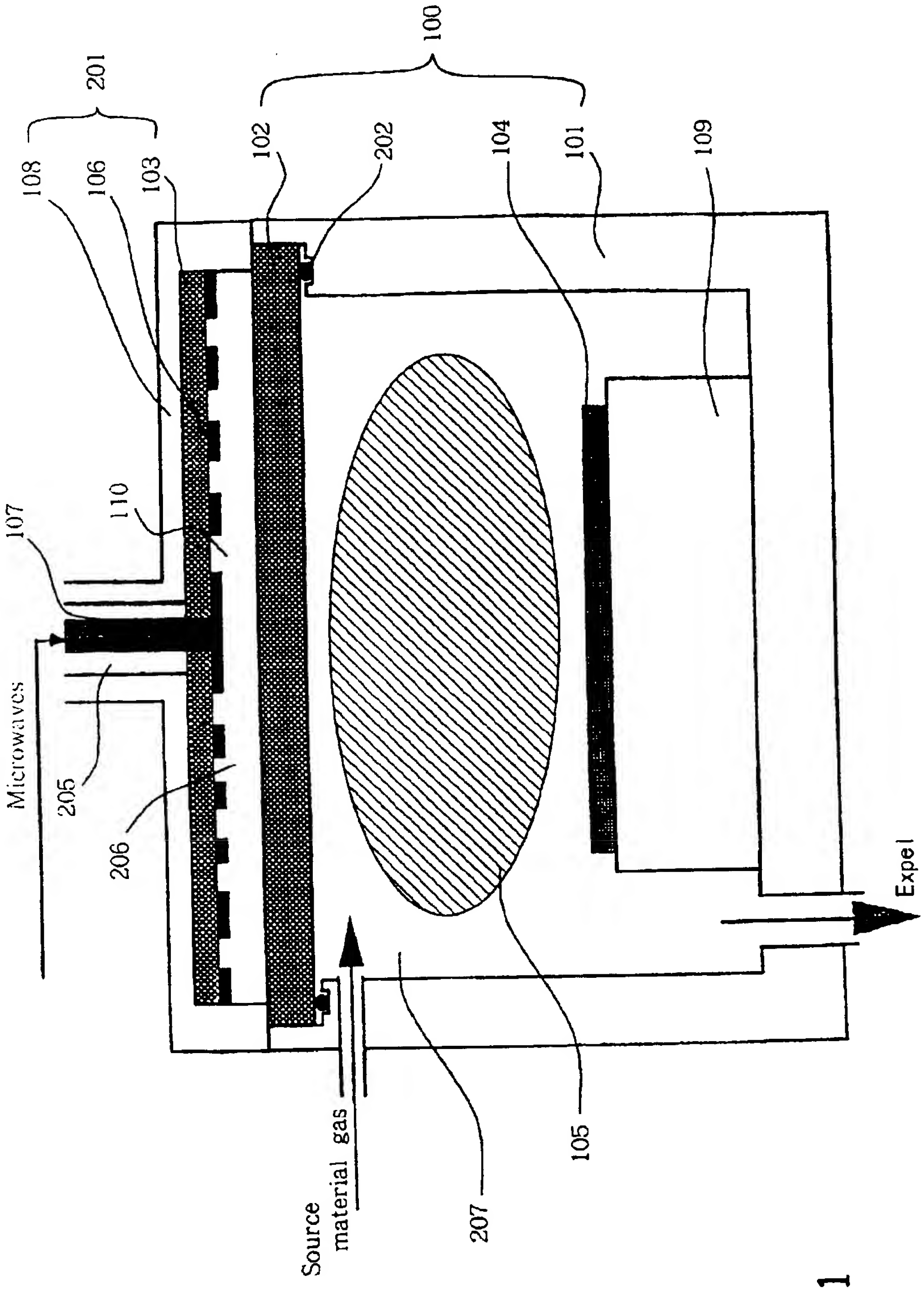
Primary Examiner—Gregory Mills
Assistant Examiner—Luz Alejandro
(74) *Attorney, Agent, or Firm*—Randall J. Knuth

(57) **ABSTRACT**

A plasma device which is provided with a container, a gas supply system, and an exhaust system. The container is composed of a first dielectric plate made of a material capable of transmitting microwaves. An antenna for radiating microwaves is located on the outside of the container, and an electrode for holding an object to be treated is located inside the container. The microwave radiating surface of the antenna and the surface of the object to be treated with plasma are positioned in parallel and opposite to each other. A wall section of the container other than that constituting the first dielectric plate is composed of a member of a material having electrical conductivity higher than that of aluminum, or the internal surface of the wall section is covered with the member. The thickness (d) of the member is larger that $(2/\mu_0\sigma)^{1/2}$, where σ, μ_0 and ω respectively represent the electrical conductivity of the member, the permeability of vacuum and the angular frequency of the microwaves radiated from the antenna.

33 Claims, 80 Drawing Sheets





100
201
108
106
103
102
202
104
101
109
110
107
Microwaves
205
206
Expel
Source material gas
207
105

Fig. 1

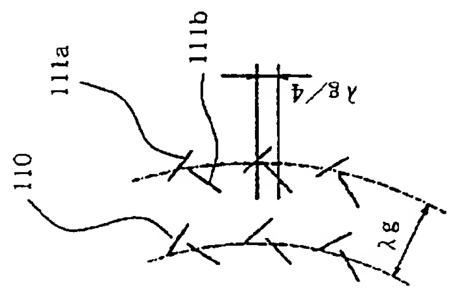


Fig. 2B

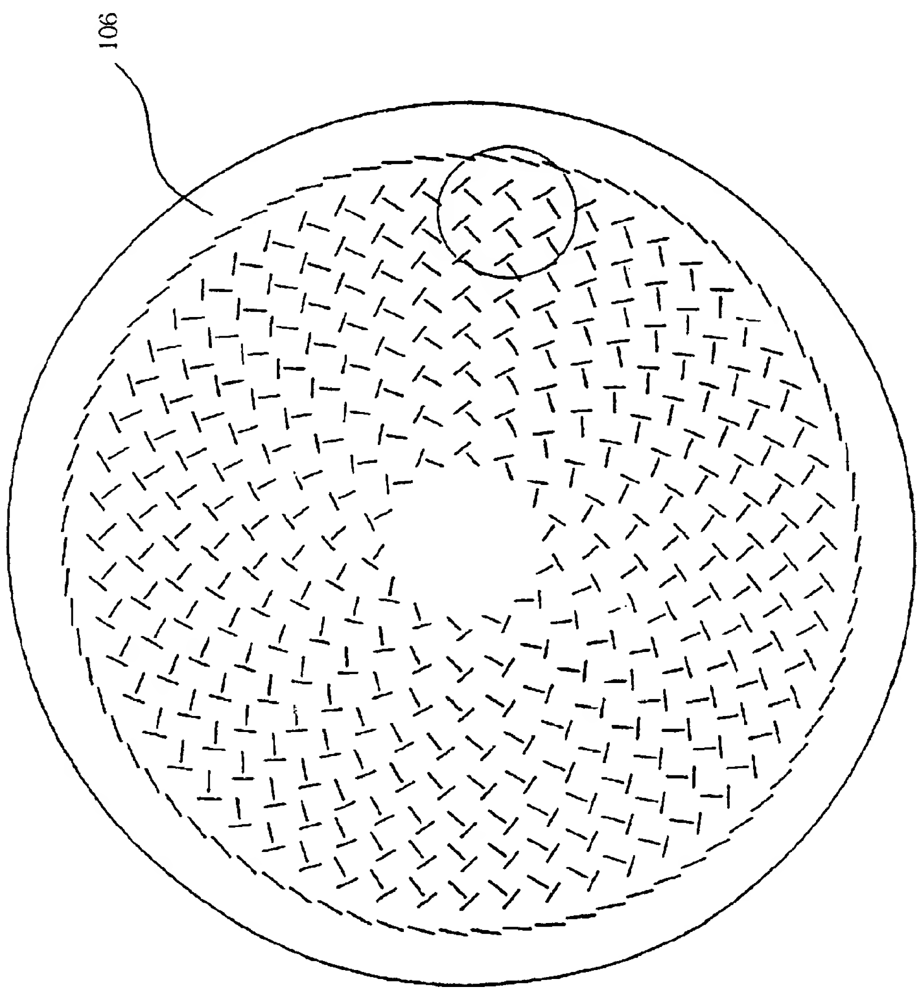


Fig. 2A

Chamber material and inner surface processing conductivity ($\Omega^{-1} \cdot m^{-1}$) \ Microwave power (W)	400	800	1200	1600
SUS (no inner surface processing) 1.4×10^6	×	×	×	×
Pb (inner surface processing onto SUS) 4.8×10^6	×	×	×	△
Ta (inner surface processing onto SUS) 8.0×10^6	×	×	○	○
W (inner surface processing onto SUS) 1.7×10^7	×	○	○	○
Al (inner surface processing onto SUS) 3.7×10^7	○	○	○	○
Au (inner surface processing onto SUS) 4.3×10^7	○	○	○	○
Cu (inner surface processing onto SUS) 6.0×10^7	○	○	○	○
Ag (inner surface processing onto SUS) 6.3×10^7	○	○	○	○

Inner surface processing thickness: 10 μm

○ plasma stable △ plasma unstable × no activation of plasma caused

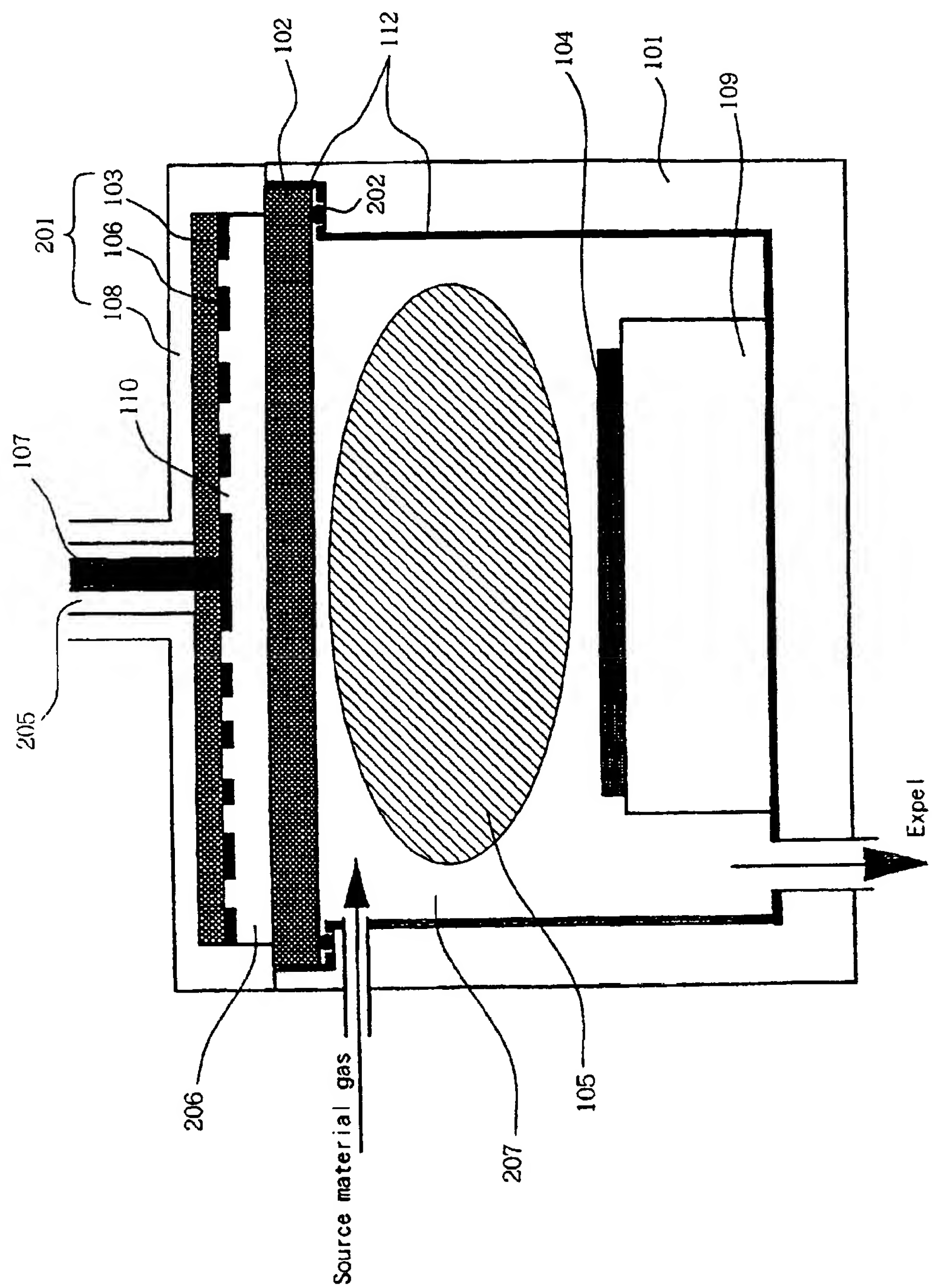
Fig. 3

Plasma generation state caused by frequency of microwaves \ Al thin film thickness(μm)	10.0	5.0	2.0	1.5	1.0	0.7	0.5	0.2
2.45GHz	○	○	○	△	△	×	×	×
8.3GHz	○	○	○	○	○	△	×	×

skin depth determined from microwave δ=(2/μΟσω)1/2 when microwave frequency is 8.3GHz(0.89μm)

skin depth determined from microwave δ=(2/μΟσω)1/2 when microwave frequency is 2.45GHz(1.67μm)

Fig. 4



102
112
104
101
109
201
103
106
108
202
110
107
205
206
Source material gas
207
105
Expel

Fig. 5

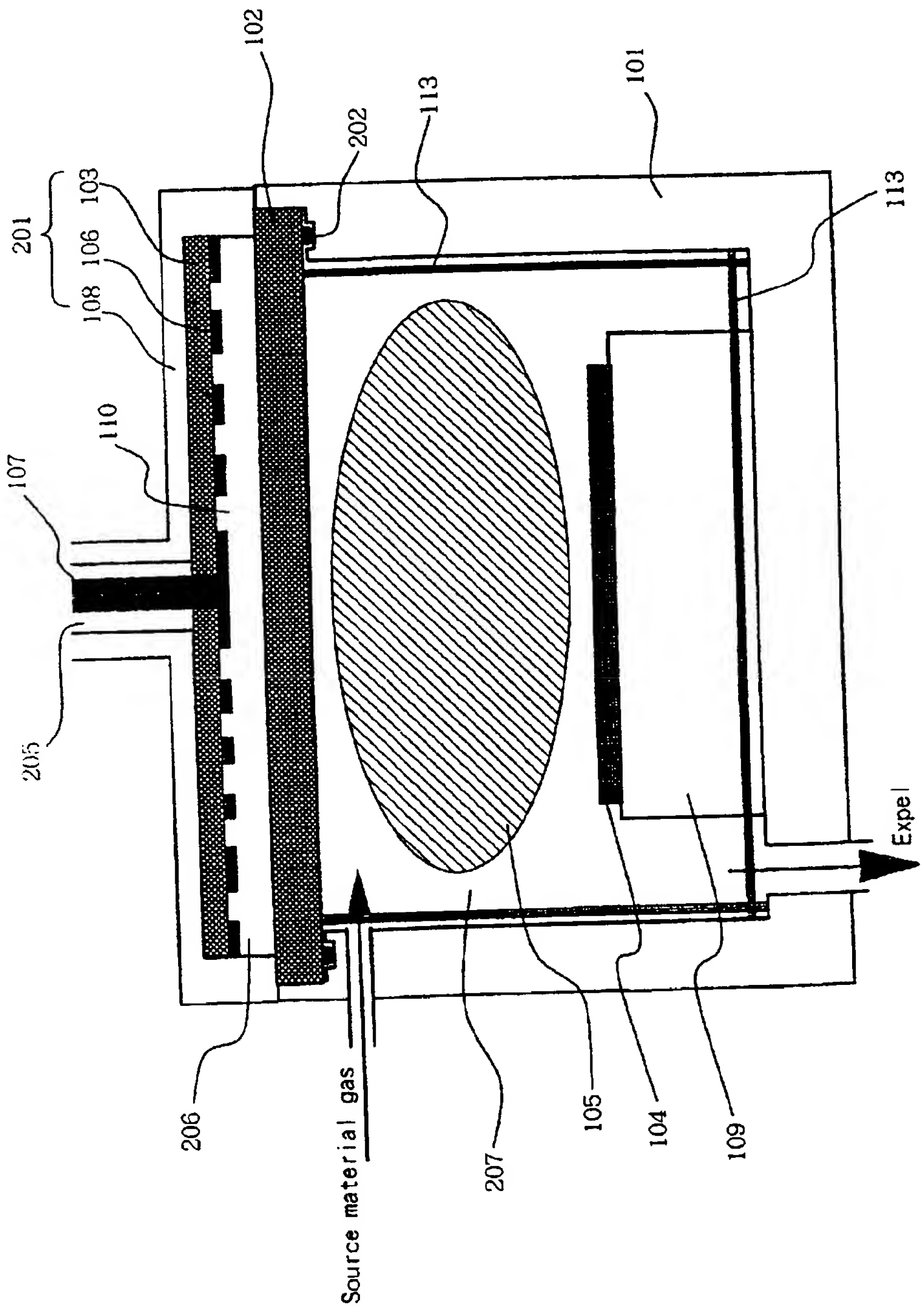

102
101
113
202
113
201
103
106
108
110
107
205
206
Source material gas
207
105
104
109
Expel

Fig. 6

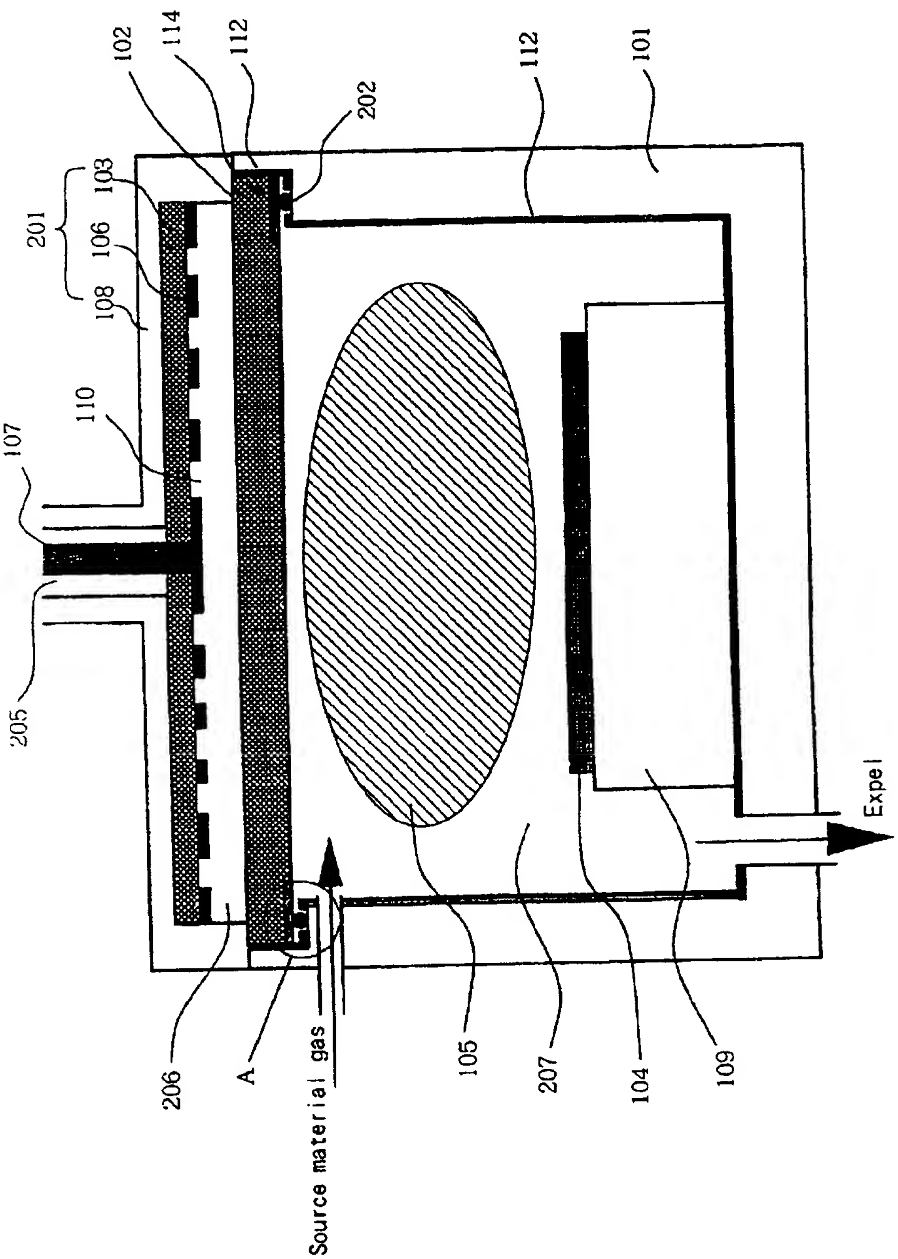

102
114
112
202
112
101
201
103
106
108
110
107
205
206
A
Source material gas
105
207
104
109
Expel

Fig. 7

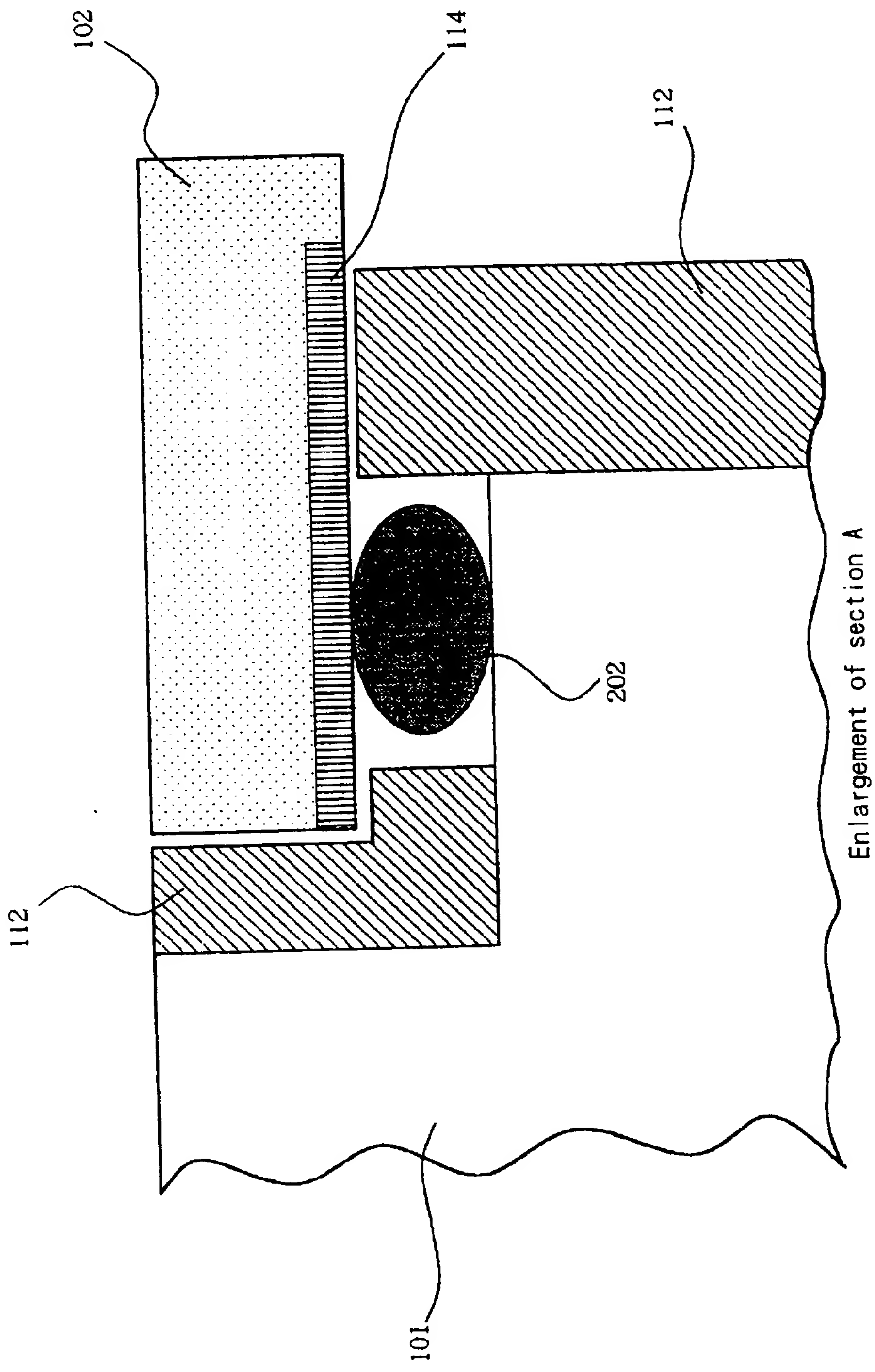


Fig. 8

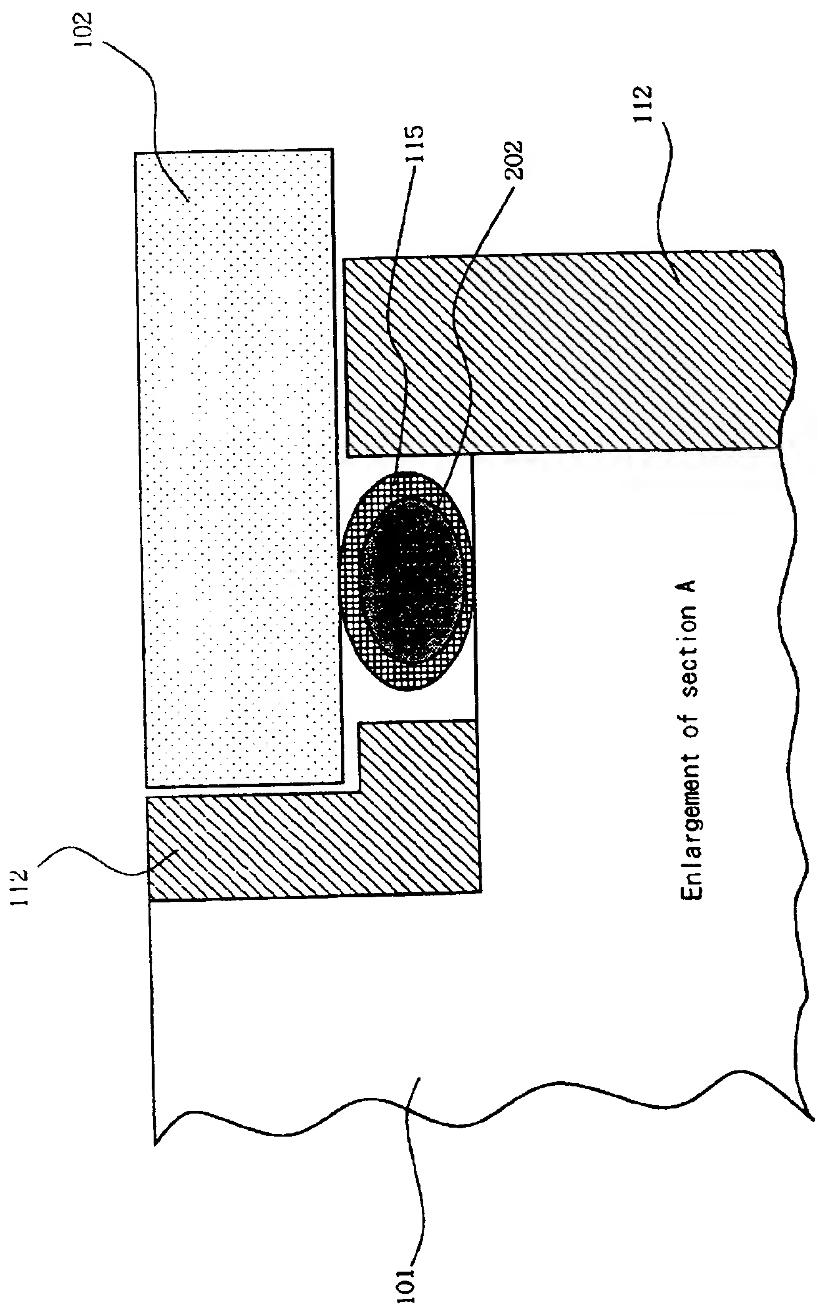


Fig. 9

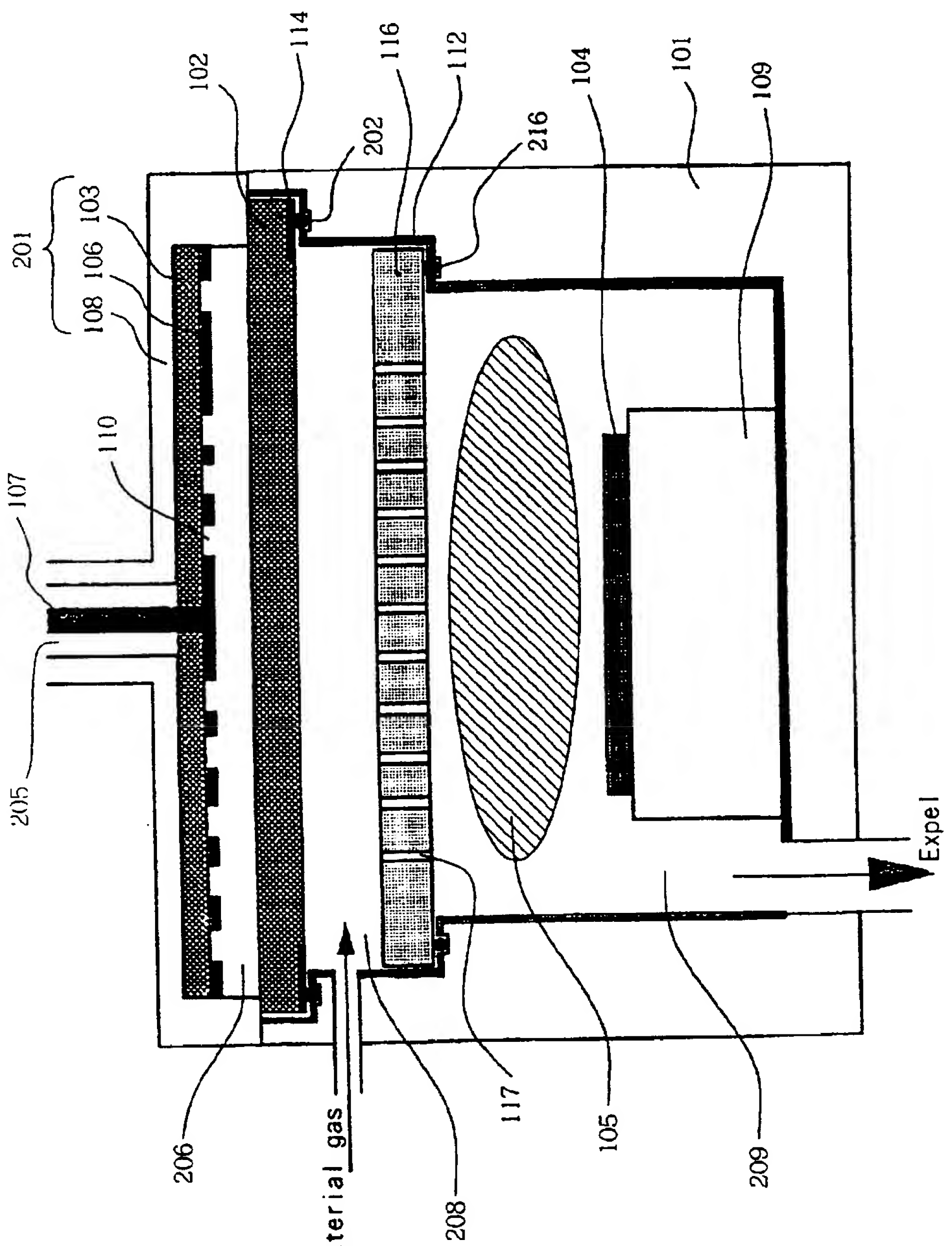

201
103
106
108
107
110
205
102
114
202
116
112
216
104
101
109
206
Source material gas
208
117
105
209
Expel

Fig. 10

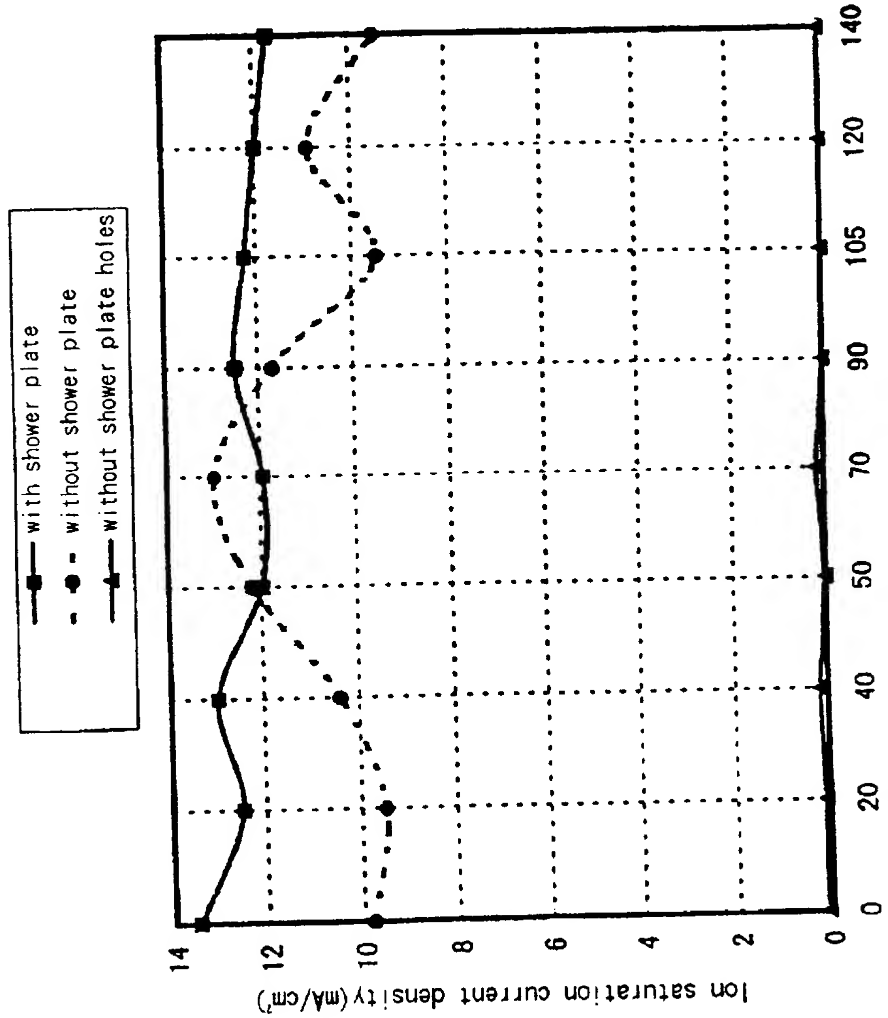

with shower plate
without shower plate
without shower plate holes
Ion saturation current density(mA/cm²)
14
12
10
8
6
4
2
0
0
20
40
50
70
90
105
120
140
Position inside base plate(distance from center)(mm)

Fig. 11

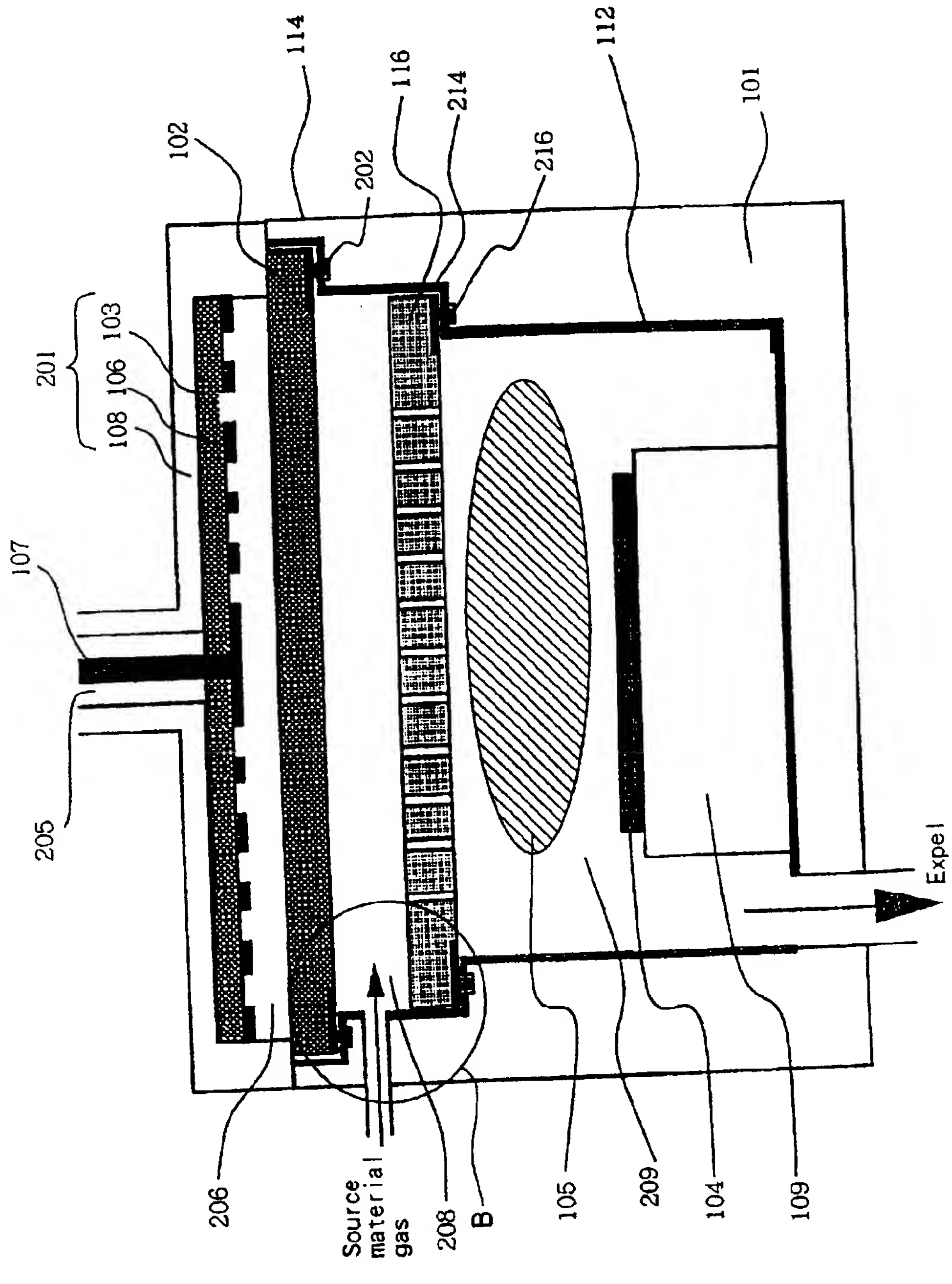

114
116
214
112
101
102
202
216
201
103
106
108
107
205
206
Source material gas
208
B
105
209
104
109
Expel

Fig. 12

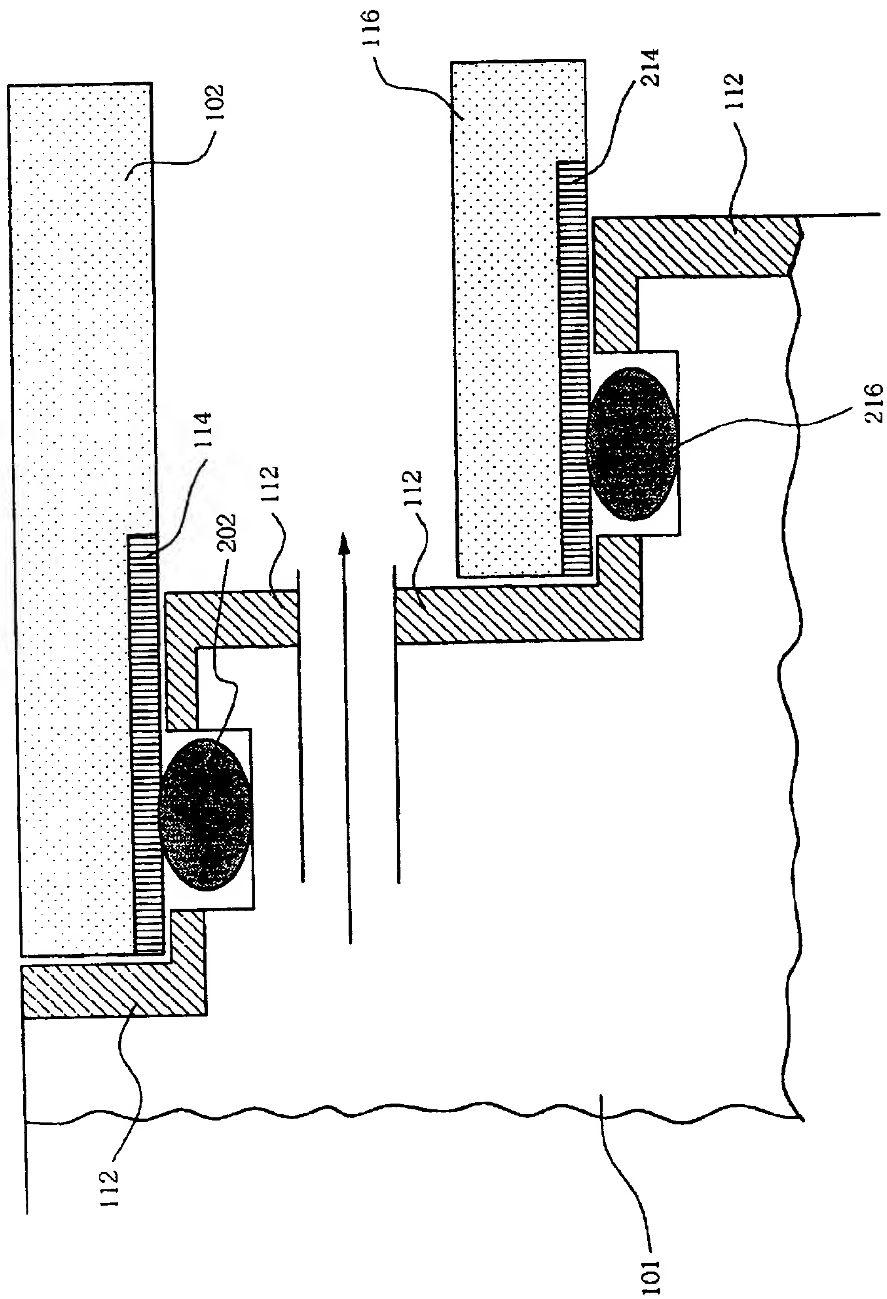


Fig. 13

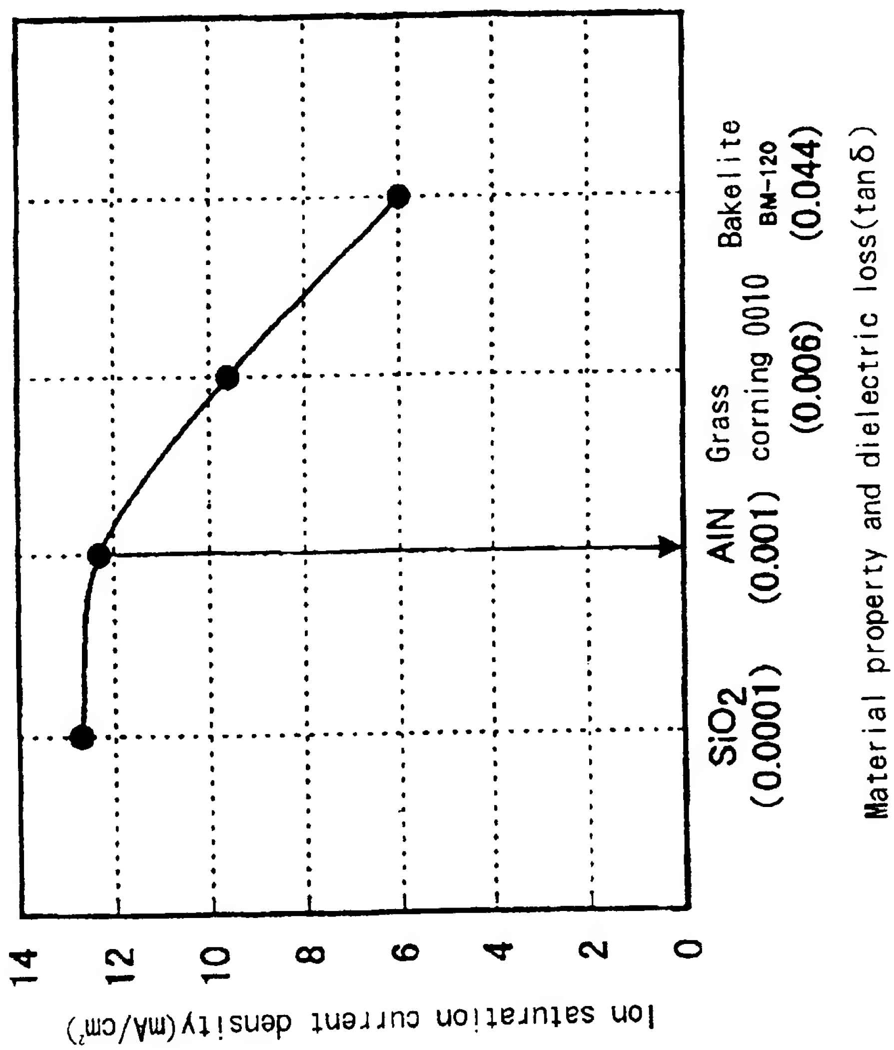
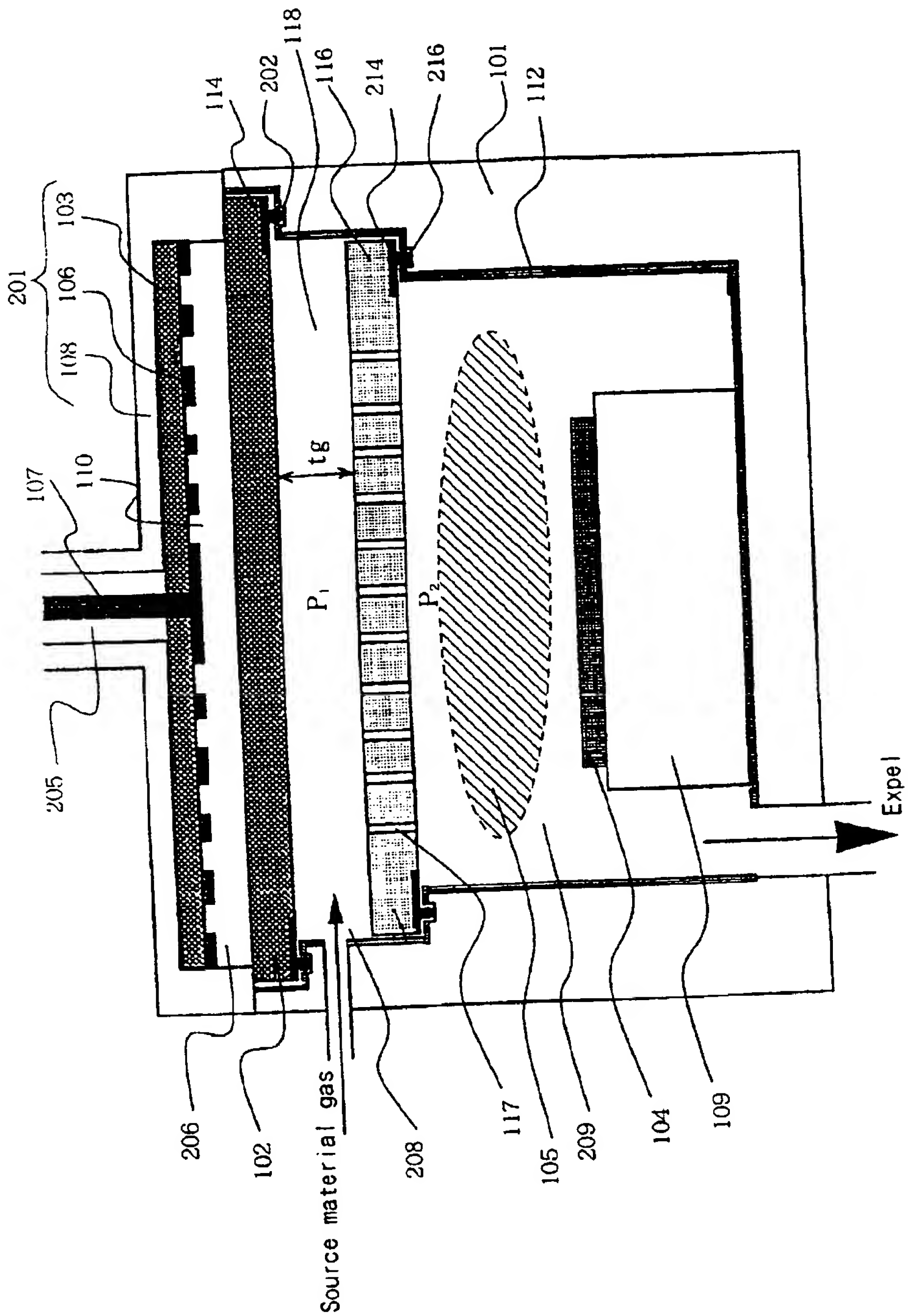

Ion saturation current density(mA/cm²)
14
12
10
8
6
4
2
0
SiO2 (0.0001)
AlN (0.001)
Grass corning 0010 (0.006)
Bakelite BM-120 (0.044)
Material property and dielectric loss(tanδ)

Fig. 14



201
103
106
108
107
110
205
114
202
118
116
214
216
101
112
tg
P1
P2
Expel
Source material gas
206
102
208
117
105
209
104
109

Fig. 15

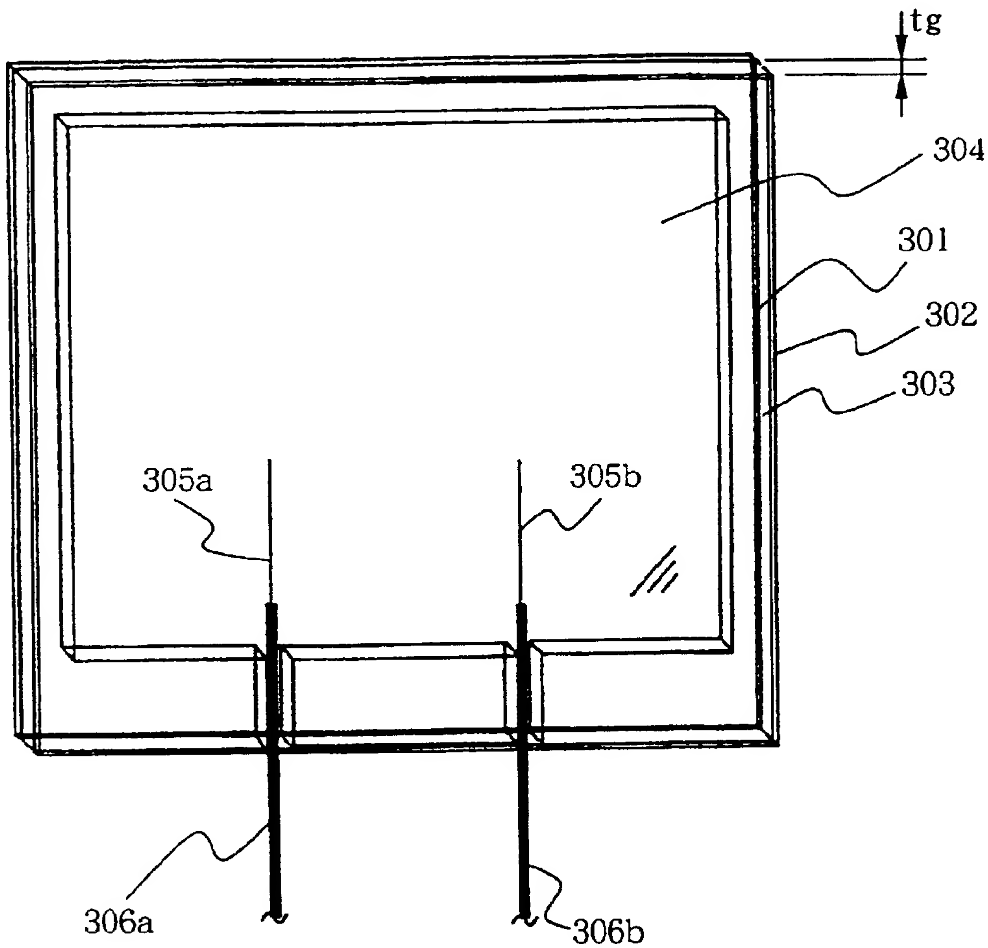
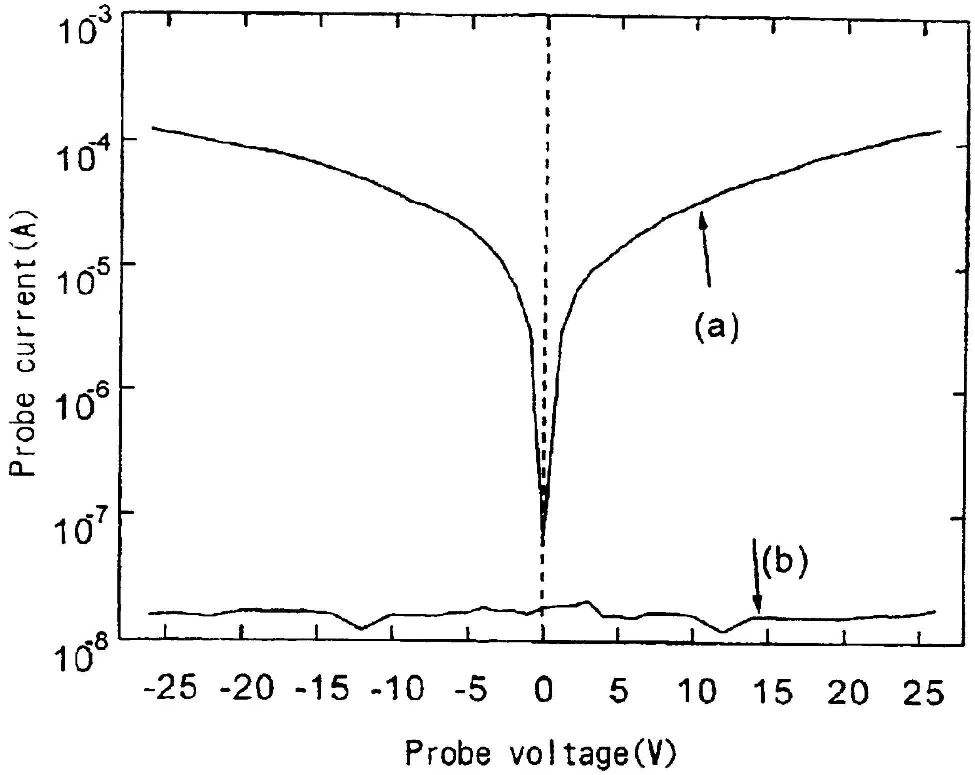


Fig. 16



10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Probe current(A)
(a)
(b)
-25 -20 -15 -10 -5 0 5 10 15 20 25
Probe voltage(V)

Fig. 17

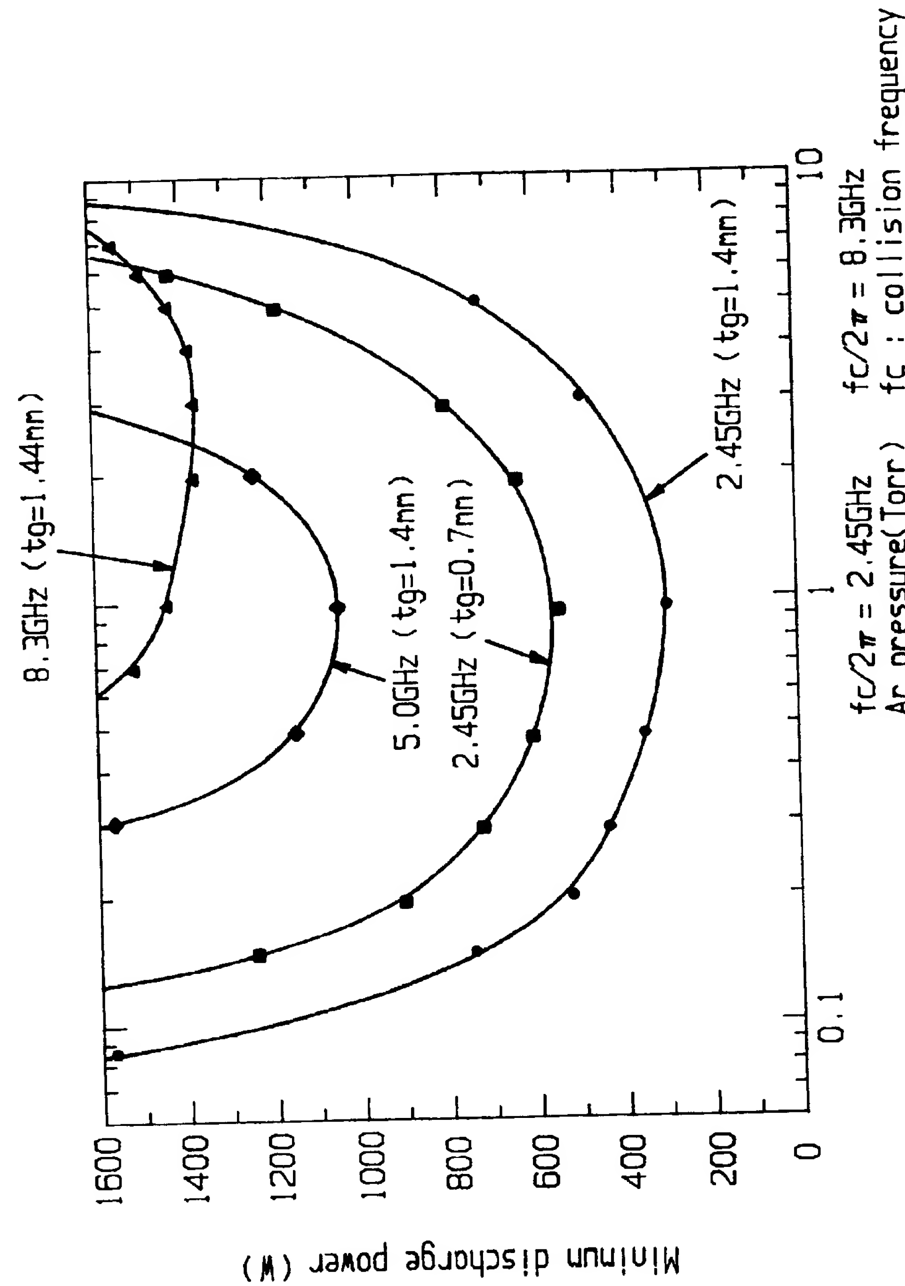

8.3GHz (tg=1.44mm)
5.0GHz (tg=1.4mm)
2.45GHz (tg=0.7mm)
2.45GHz (tg=1.4mm)
Minimum discharge power (W)
1600
1400
1200
1000
800
600
400
200
0
0.1
1
10
fc/2π = 2.45GHz
fc/2π = 8.3GHz
Ar pressure(Torr)
fc : collision frequency
(0.5eV,Ar)

Fig. 18

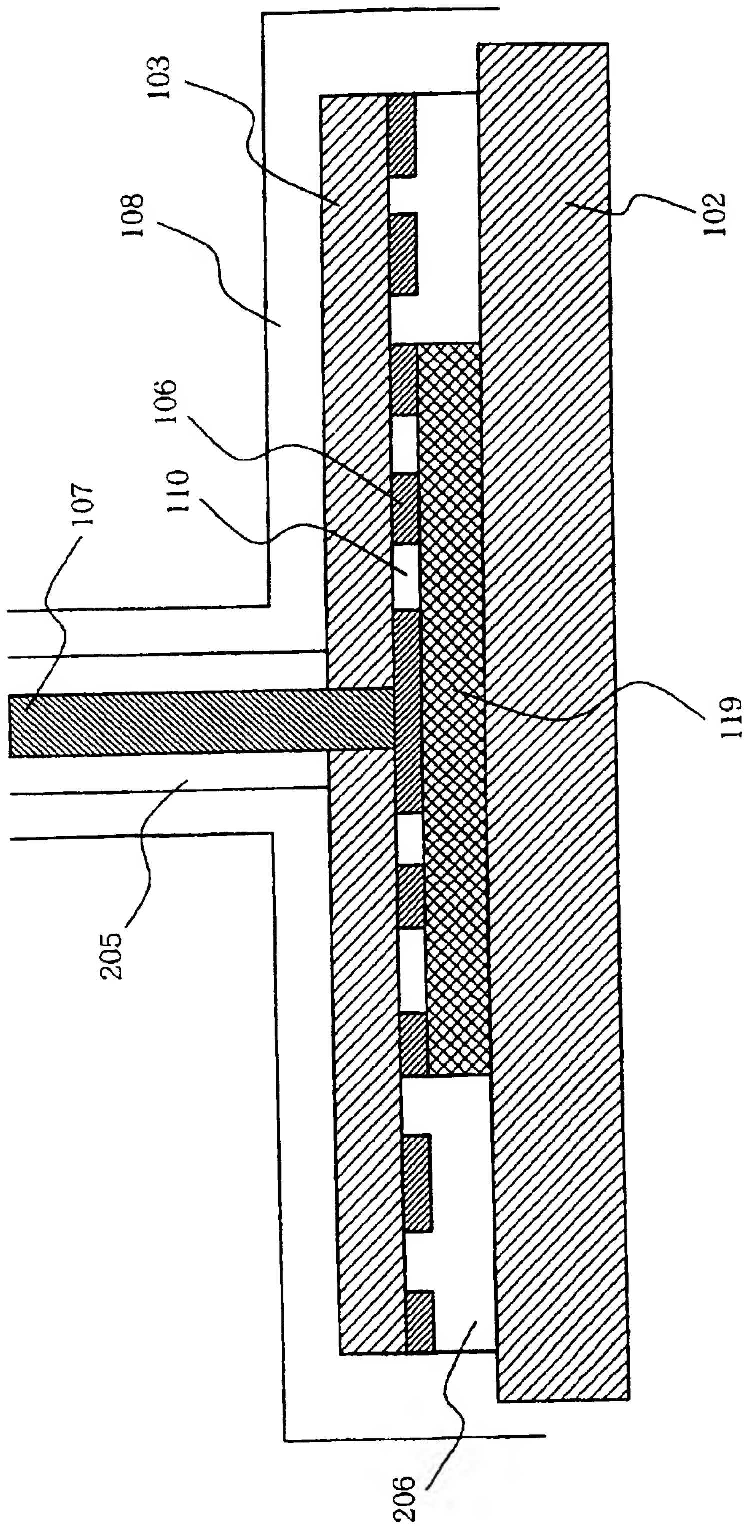


Fig. 19

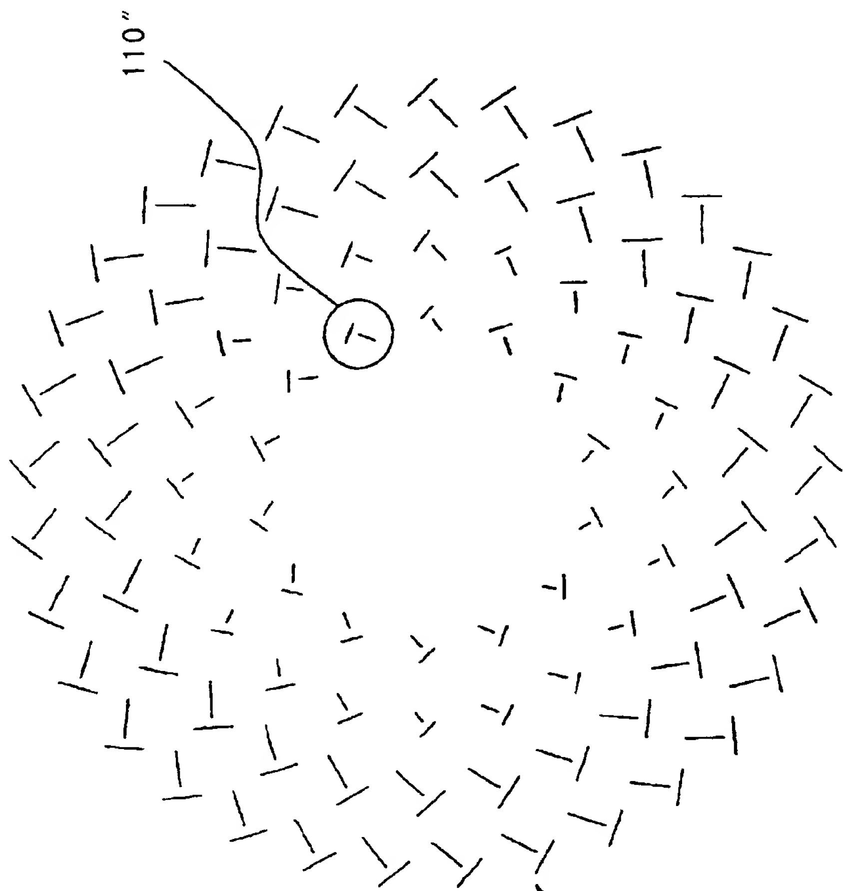


Fig. 20B

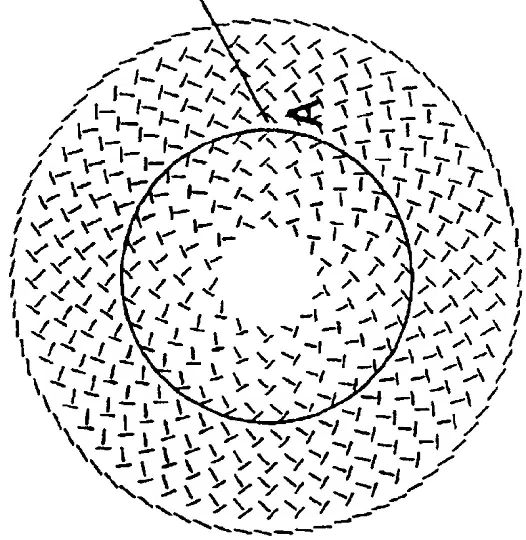


Fig. 20A

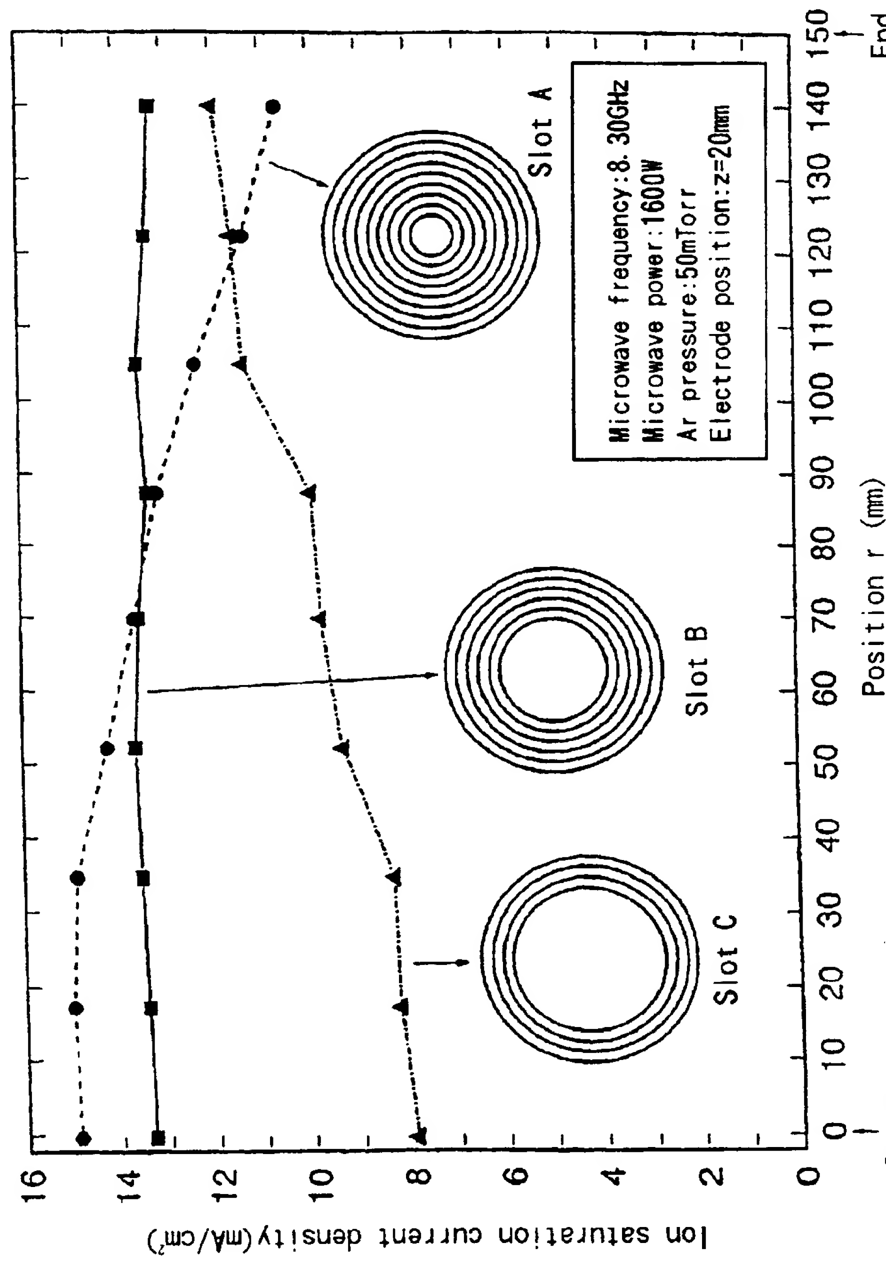

Ion saturation current density(mA/cm²)
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Center
End
Position r (mm)
Slot A
Slot B
Slot C
Microwave frequency:8. 30GHz
Microwave power:1600W
Ar pressure:50mTorr
Electrode position:z=20mm

Fig. 21

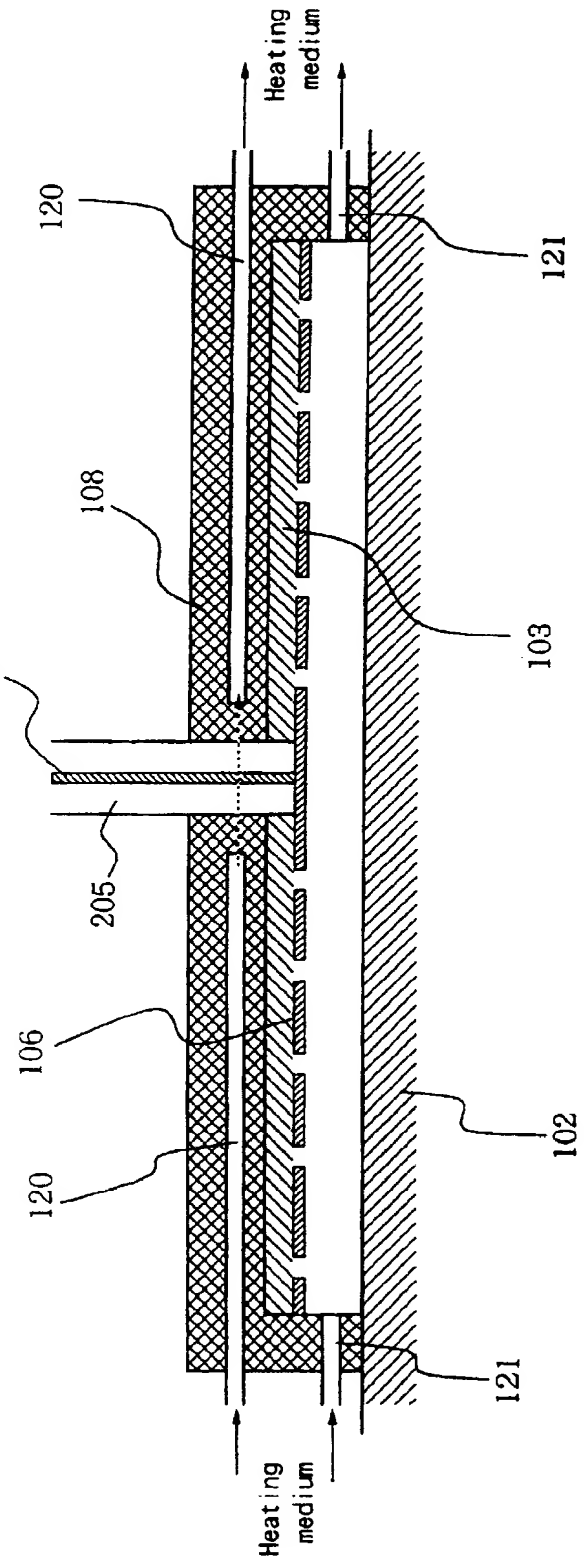

Heating medium
120
121
108
103
107
205
106
120
102
121
Heating medium

Fig. 22

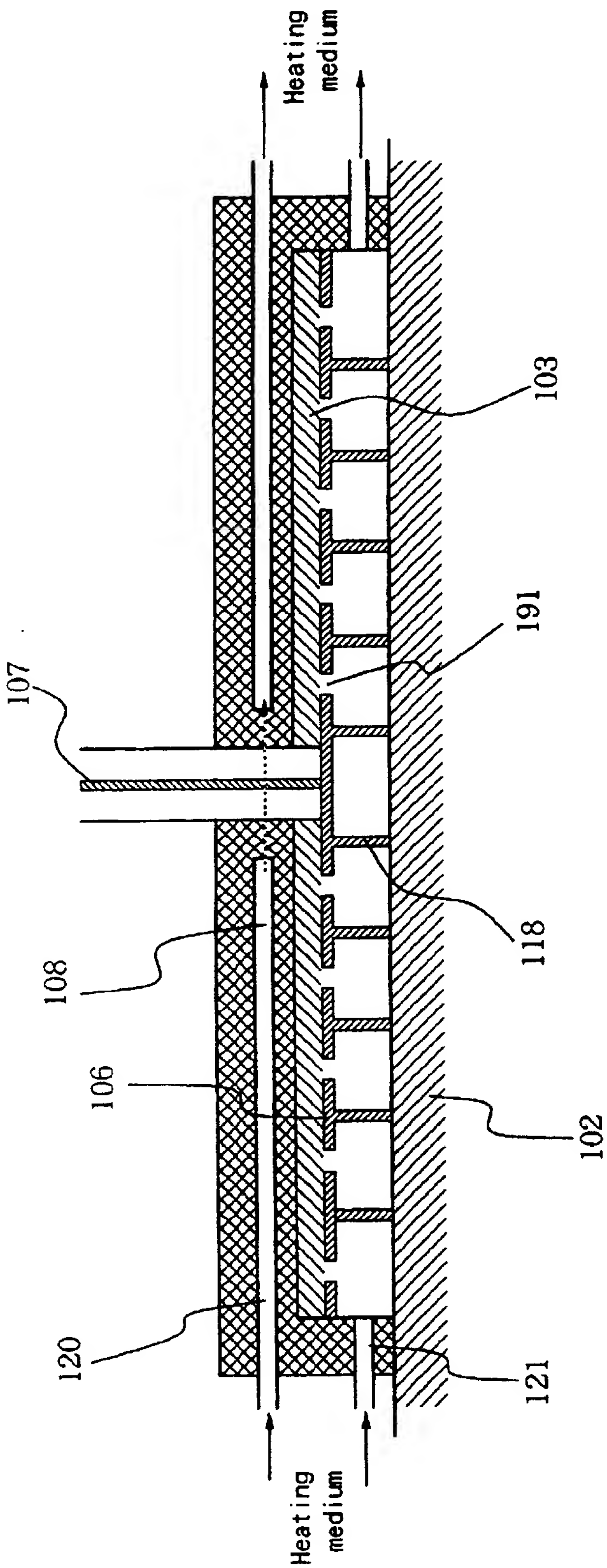
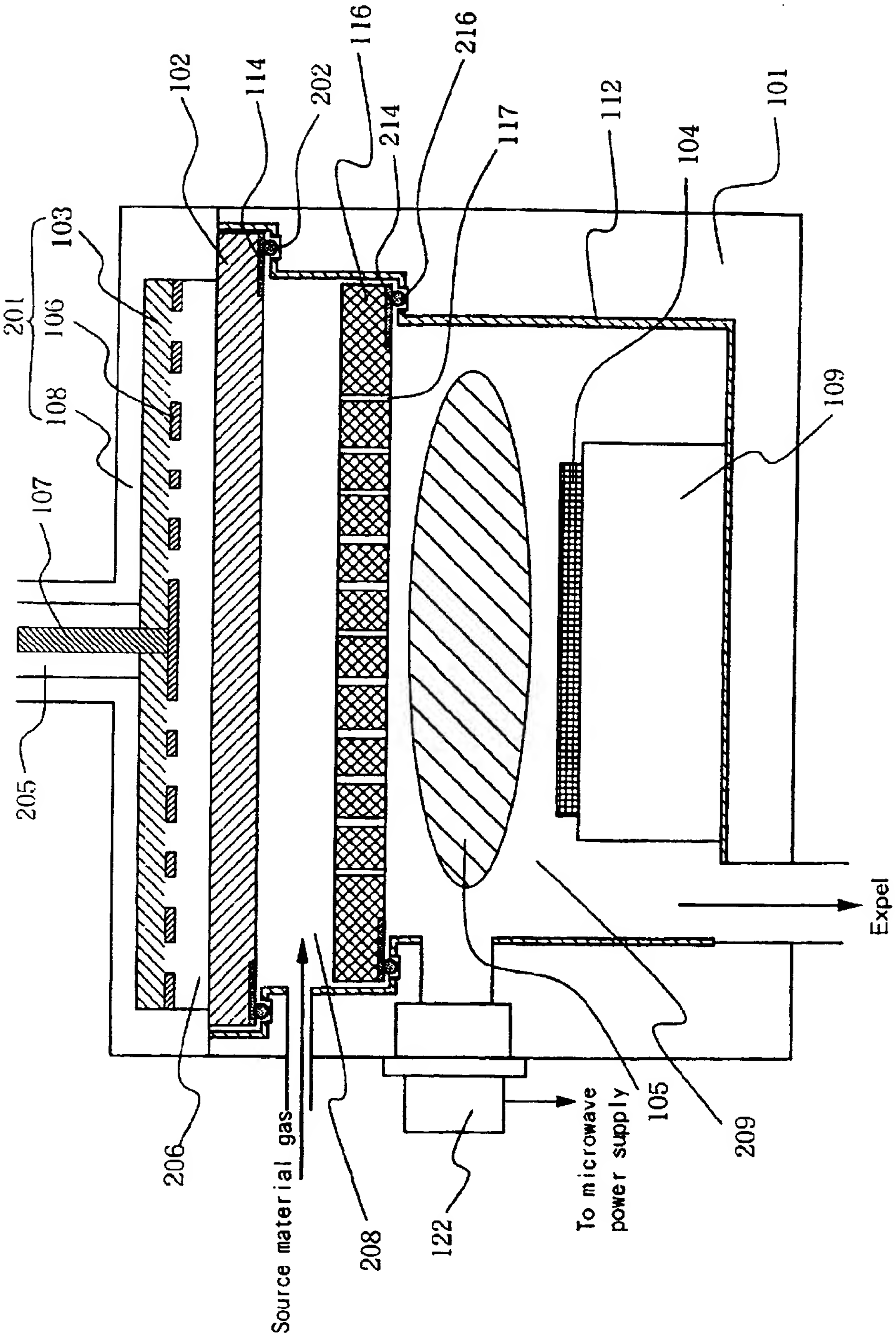

Heating medium
Heating medium
107
103
191
118
108
106
102
120
121

Fig. 23



101
102
103
104
105
106
107
108
109
112
114
116
117
122
201
202
205
206
208
209
214
216
Source material gas
To microwave power supply
Expel

Fig. 24

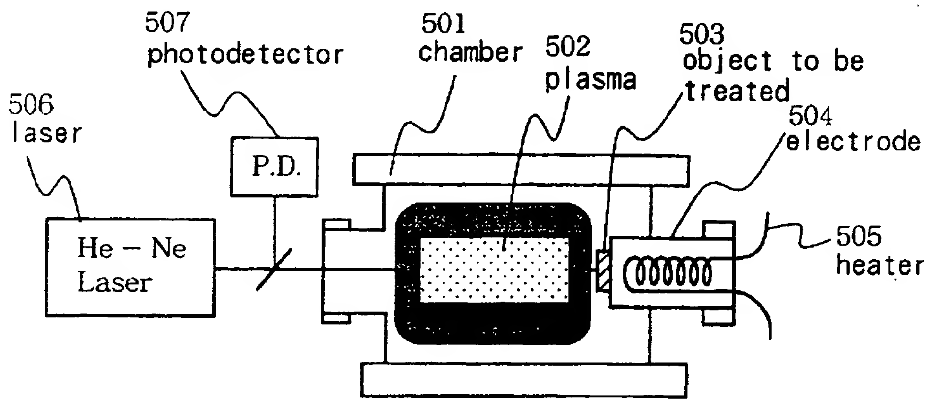

507
photodetector
501
chamber
502
plasma
503
object to be
treated
504
electrode
506
laser
P.D.
He – Ne
Laser
505
heater

Fig. 25

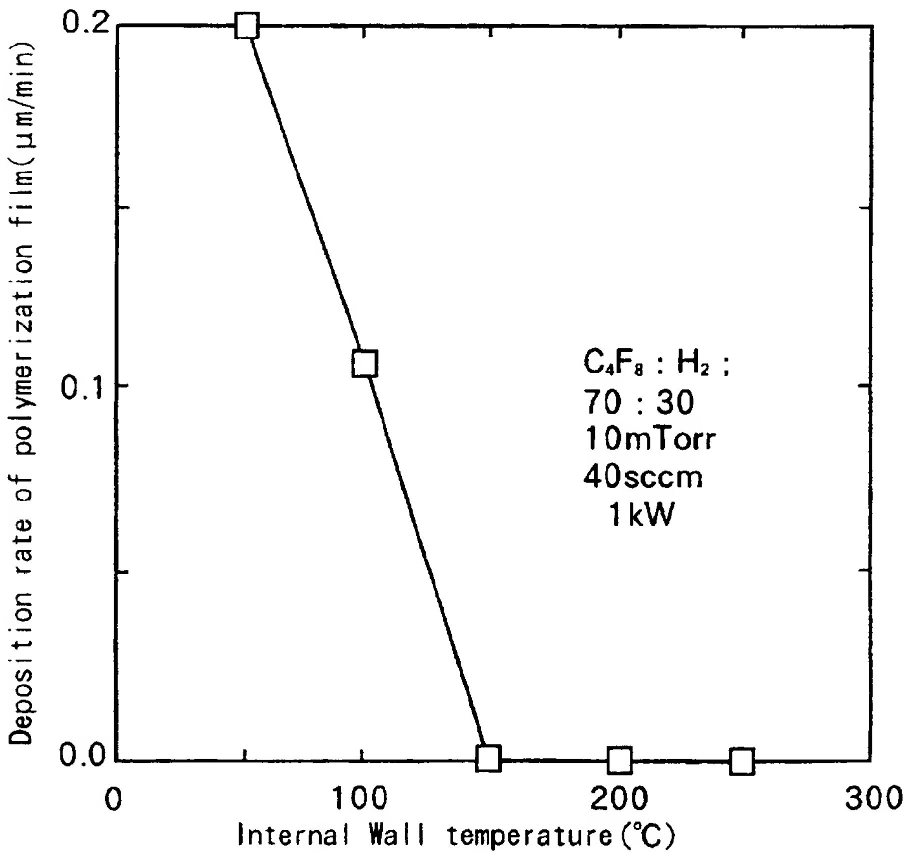

0.2
0.1
0.0
Deposition rate of polymerization film(μm/min)
0
100
200
300
Internal Wall temperature(℃)
C4F8 : H2 ;
70 : 30
10mTorr
40sccm
1kW

Fig. 26

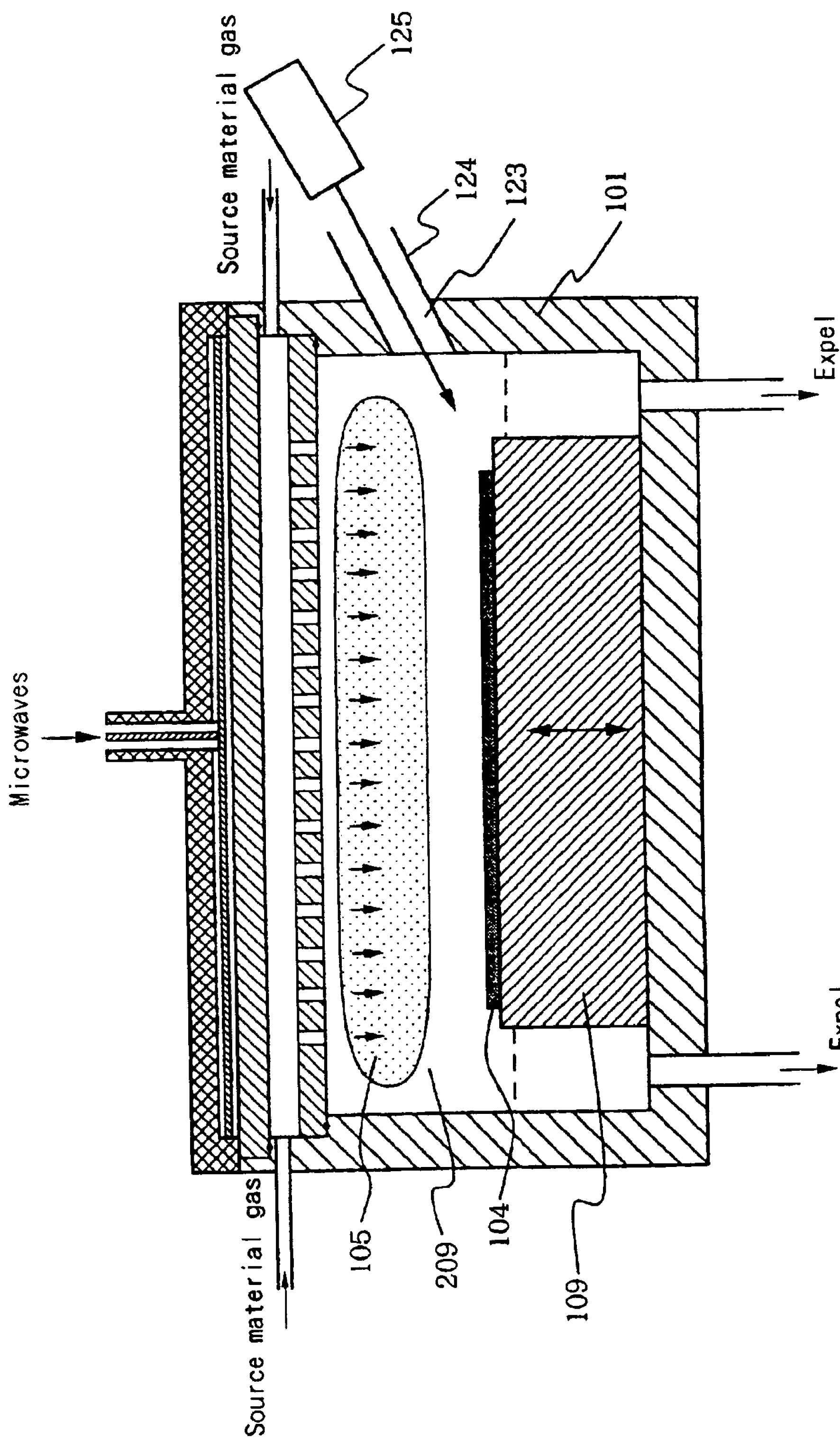
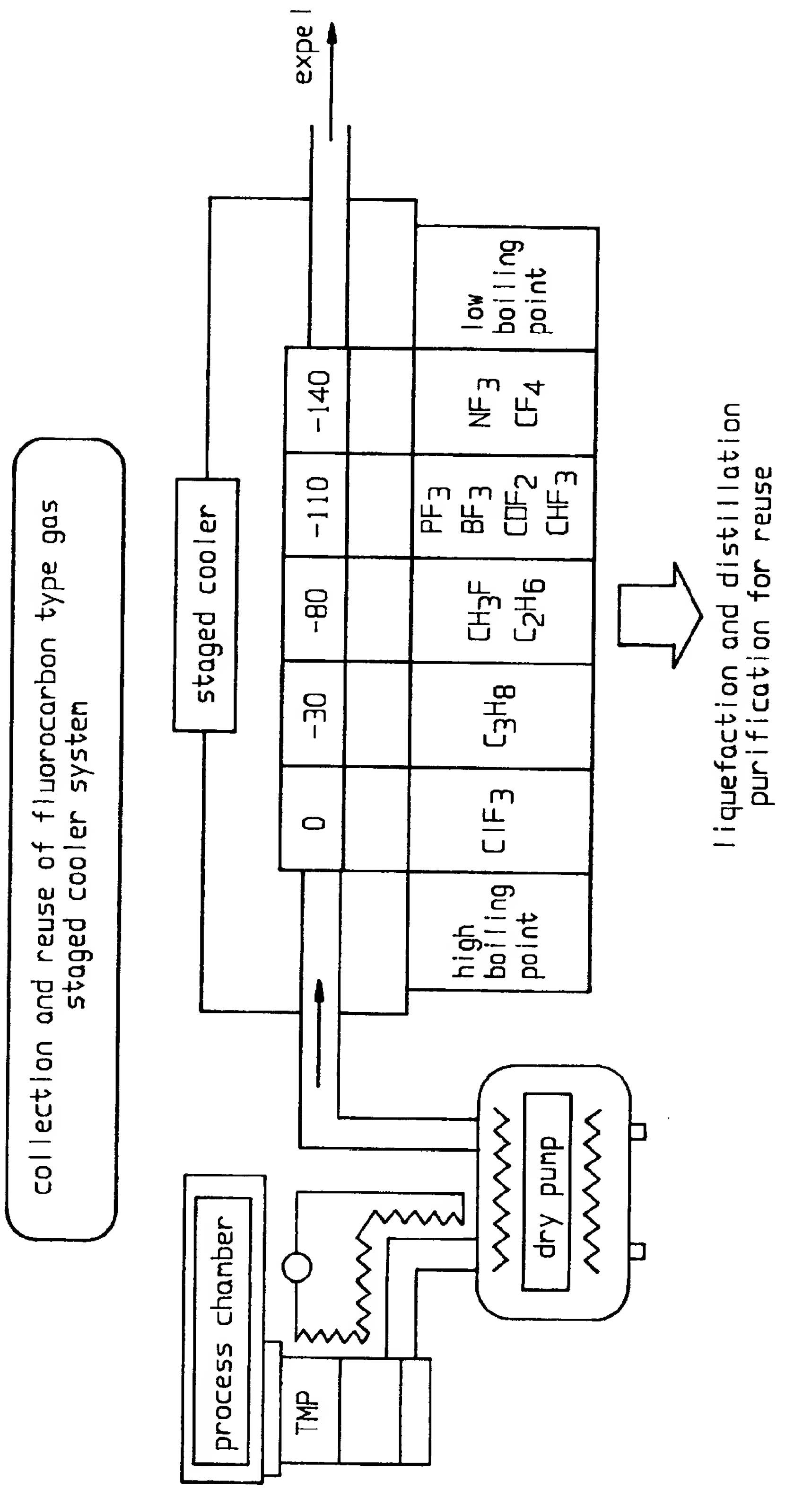

Source material gas
125
124
123
101
Expel
Microwaves
Expel
Source material gas
105
209
104
109

Fig. 27



global warning effects of fluorocarbon are 100,000 - 1,000,000 greater than CO_2

Fig. 28

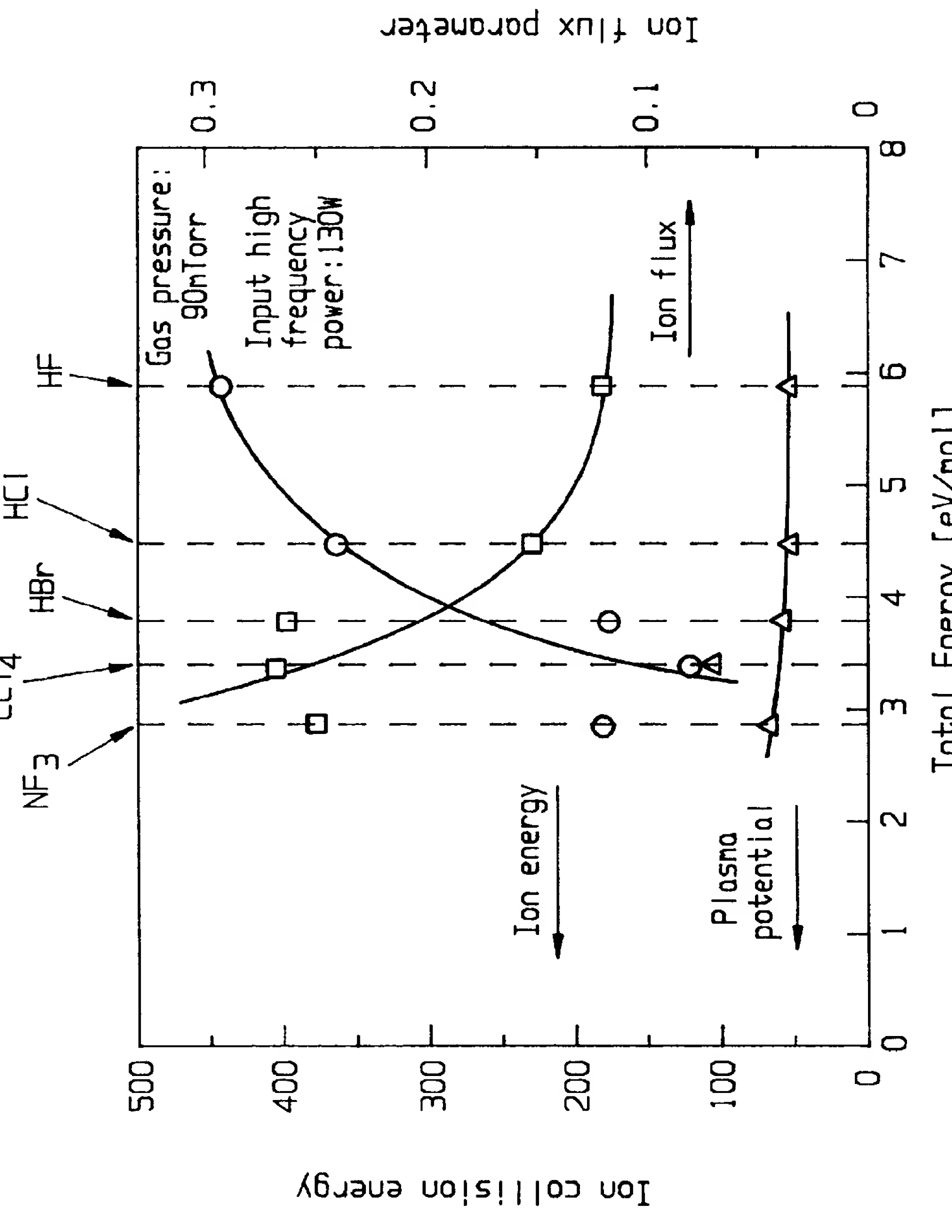

Ion flux parameter
0.3
0.2
0.1
0
Gas pressure: 90mTorr
Input high frequency power:130W
Ion flux
HF
HCl
HBr
CCl_4
NF_3
Ion energy
Plasma potential
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
Total Energy [eV/mol]
Ion collision energy

Fig. 29

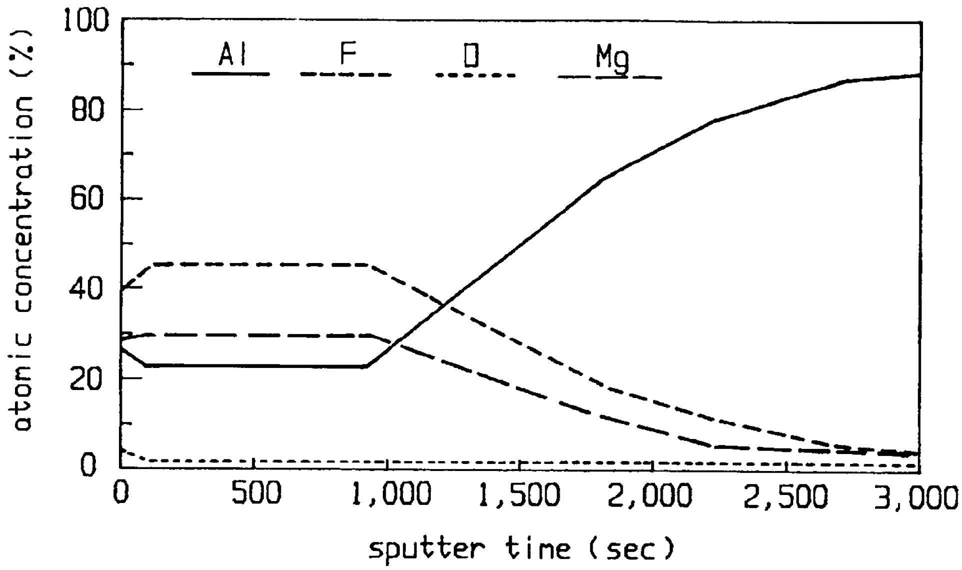


Fig. 30A

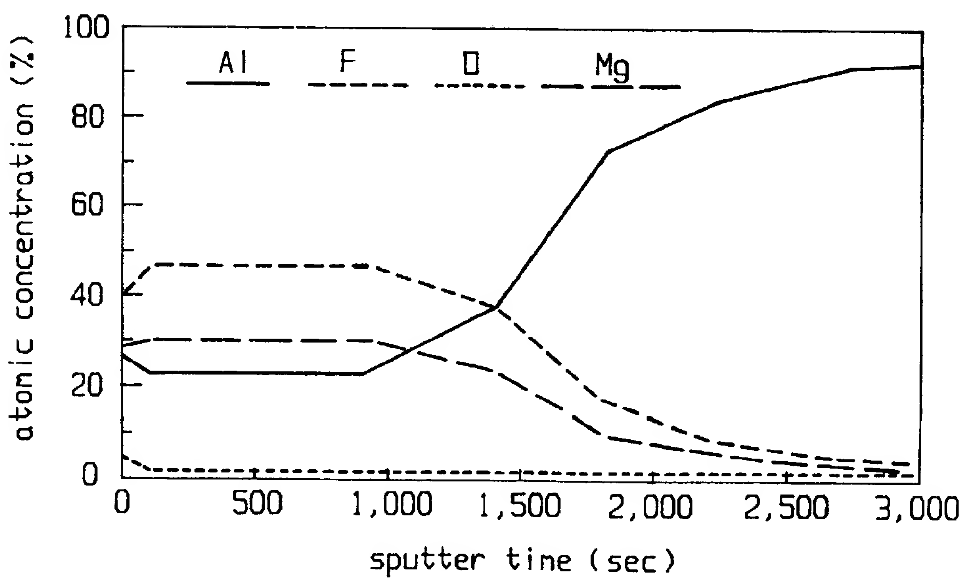


Fig. 30B

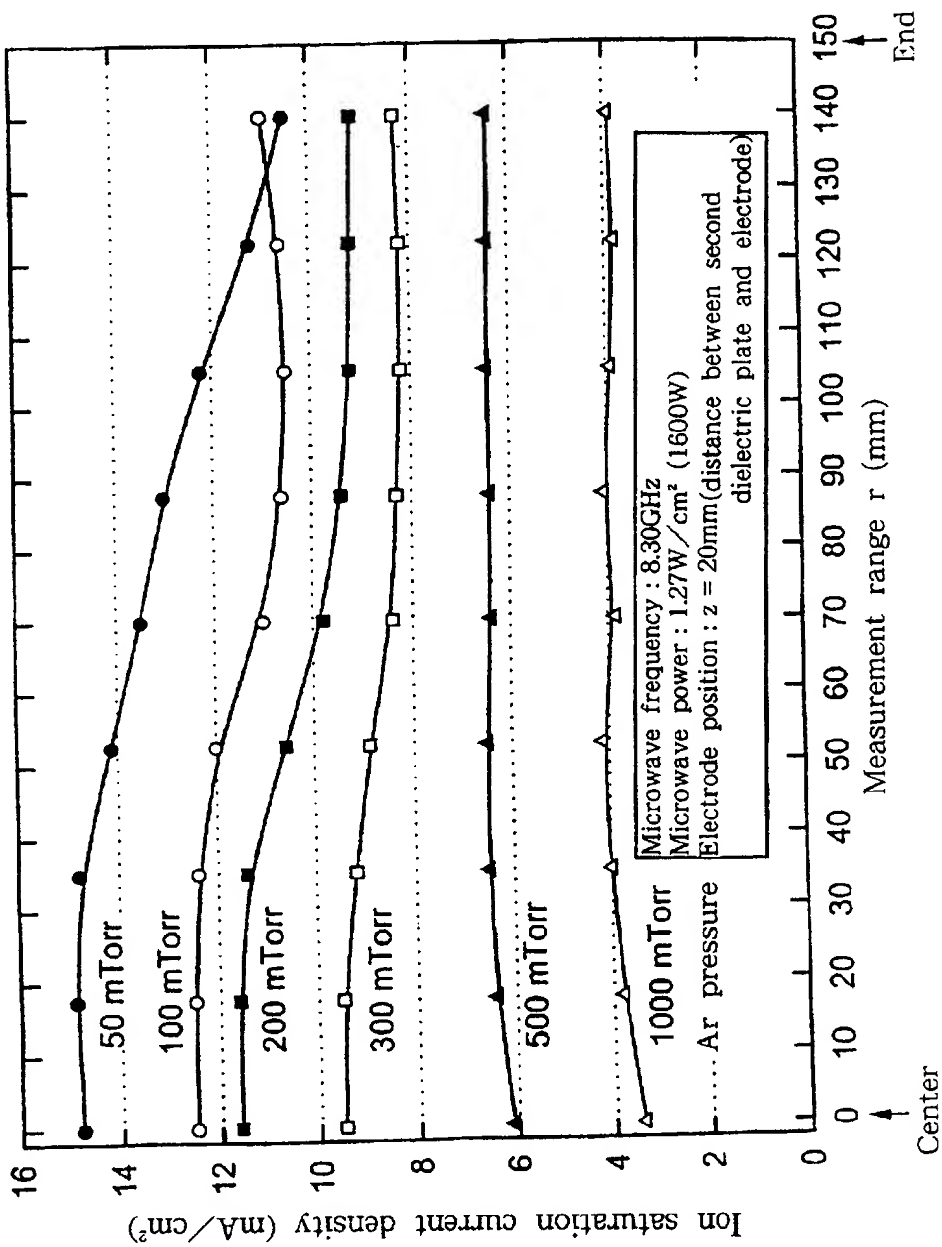

Ion saturation current density (mA/cm²)
Measurement range r (mm)
Center
End
50 mTorr
100 mTorr
200 mTorr
300 mTorr
500 mTorr
1000 mTorr
Ar pressure
Microwave frequency : 8.30GHz
Microwave power : 1.27W/cm² (1600W)
Electrode position : z = 20mm(distance between second dielectric plate and electrode)
0
2
4
6
8
10
12
14
16
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

Fig. 31

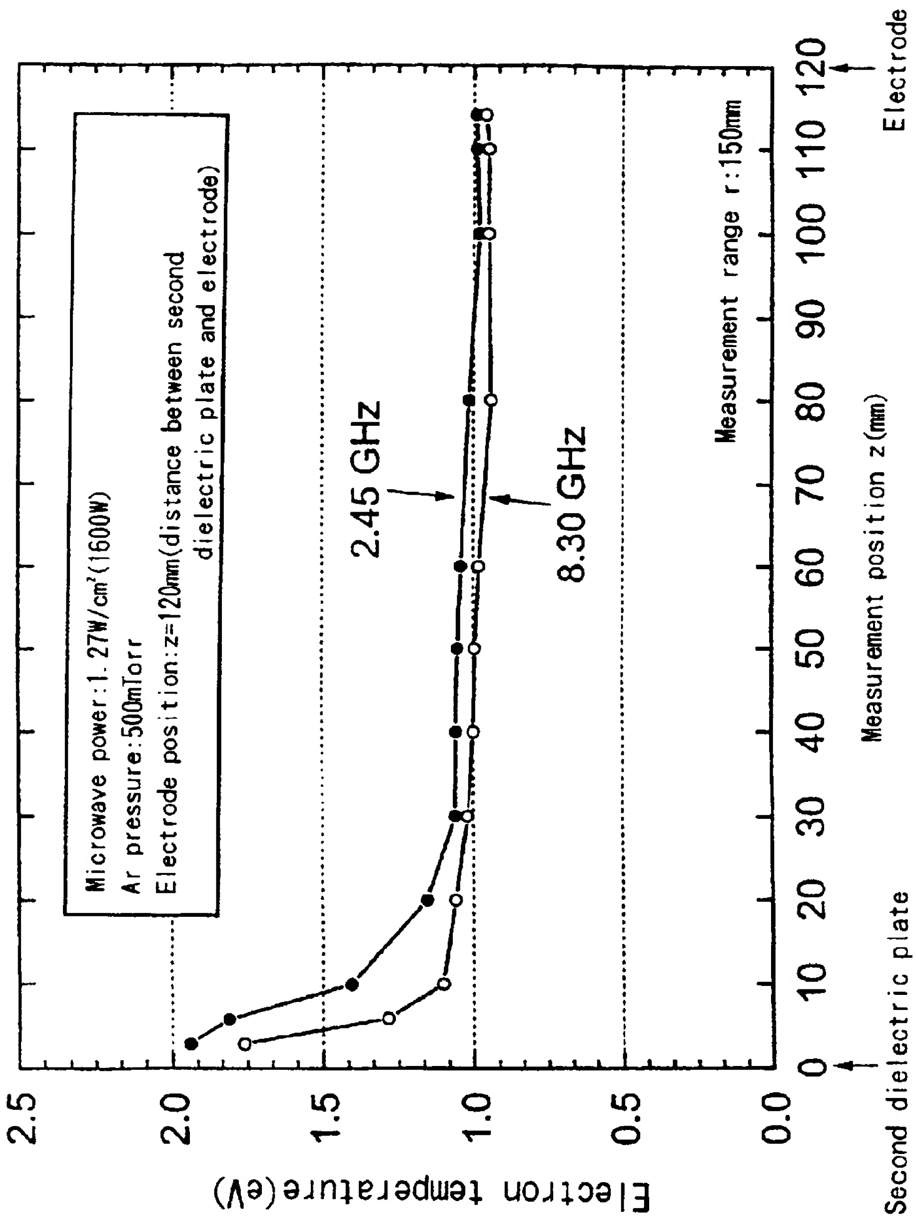

Microwave power:1.27W/cm²(1600W)
Ar pressure:500mTorr
Electrode position:z=120mm(distance between second dielectric plate and electrode)
2.45 GHz
8.30 GHz
Measurement range r:150mm
Electron temperature(eV)
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
60
70
80
90
100
110
120
Second dielectric plate
Electrode
Measurement position z(mm)

Fig. 32

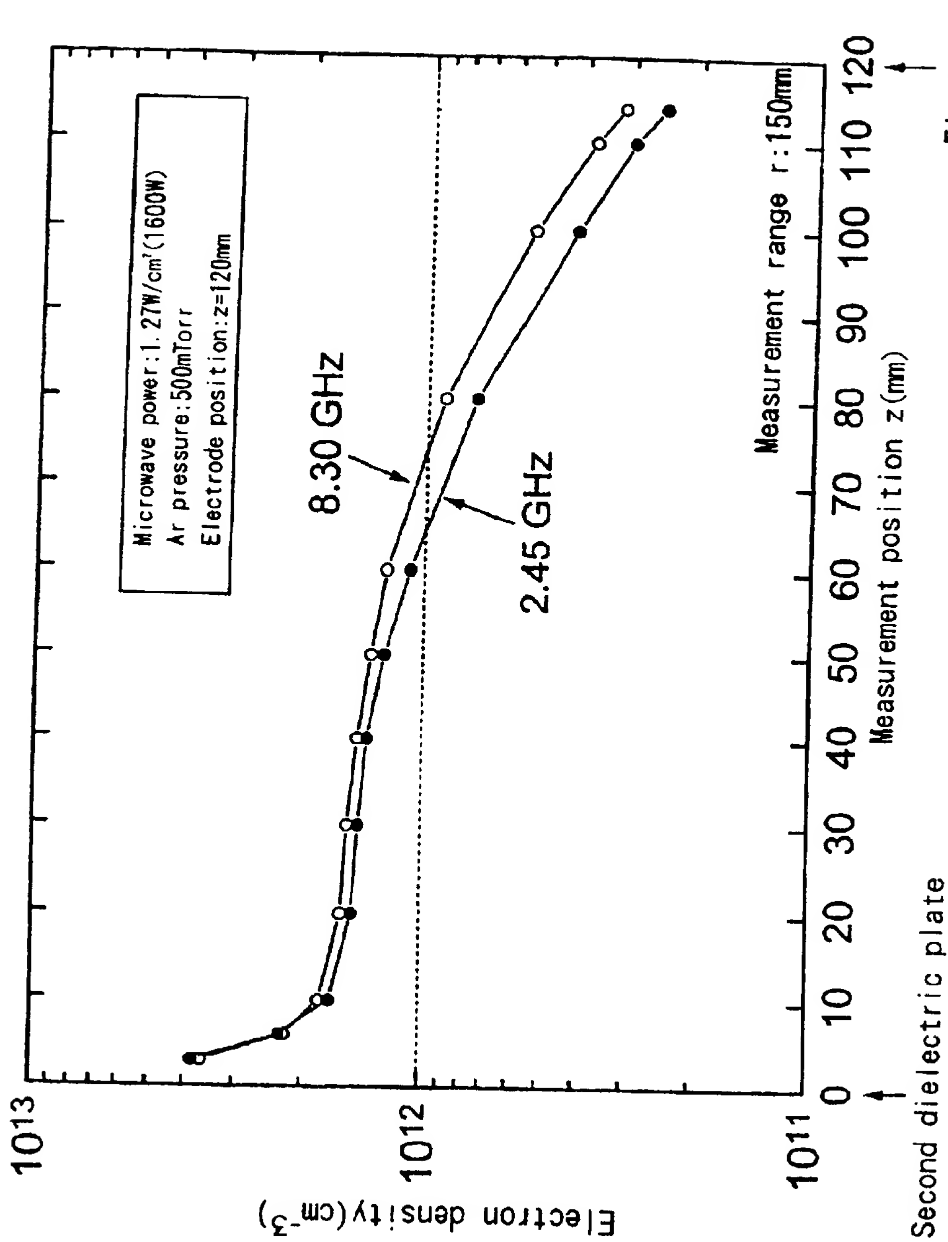

Microwave power:1.27W/cm²(1600W)
Ar pressure:500mTorr
Electrode position:z=120mm
8.30 GHz
2.45 GHz
Measurement range r:150mm
Electron density(cm⁻³)
1013
1012
1011
0
10
20
30
40
50
60
70
80
90
100
110
120
Measurement position z(mm)
Second dielectric plate
Electrode

Fig. 33

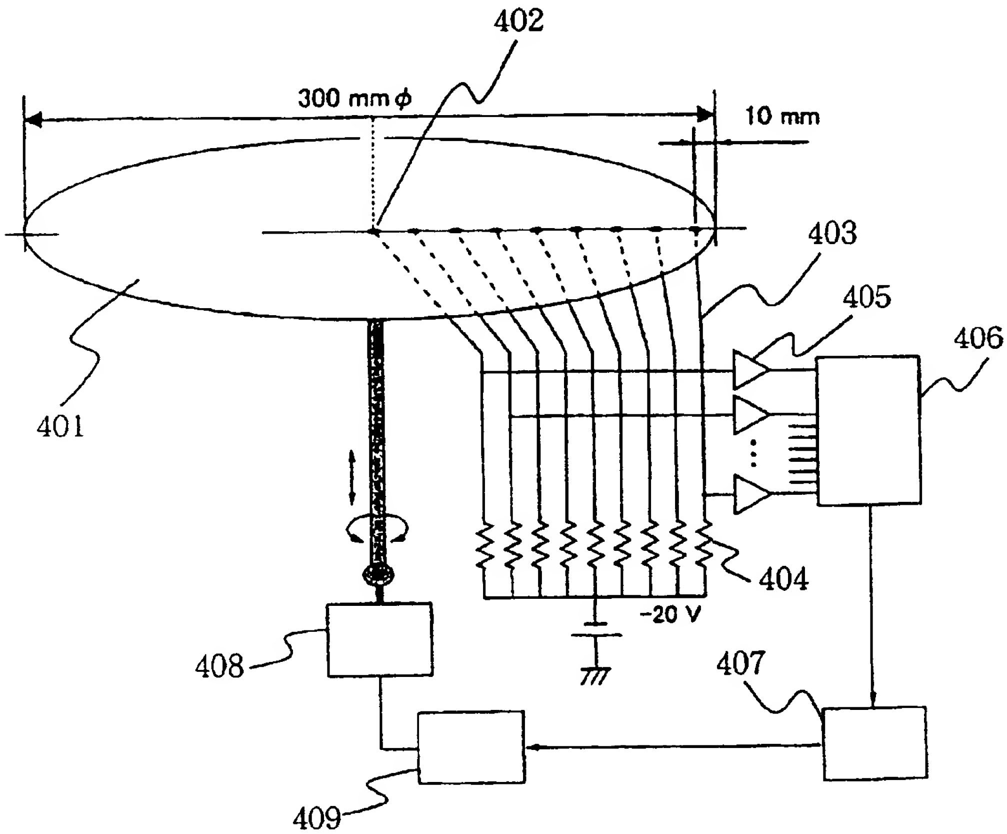


Fig. 34

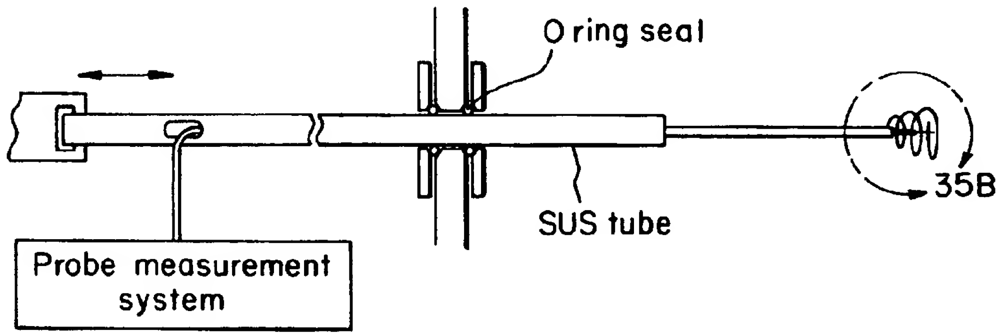


Fig. 35A

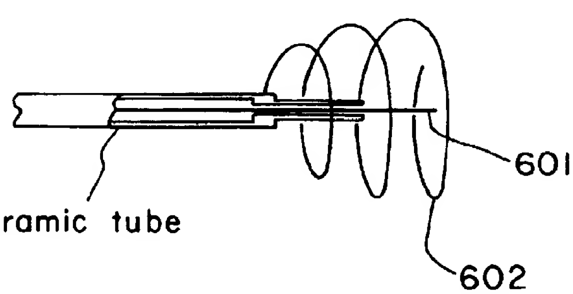
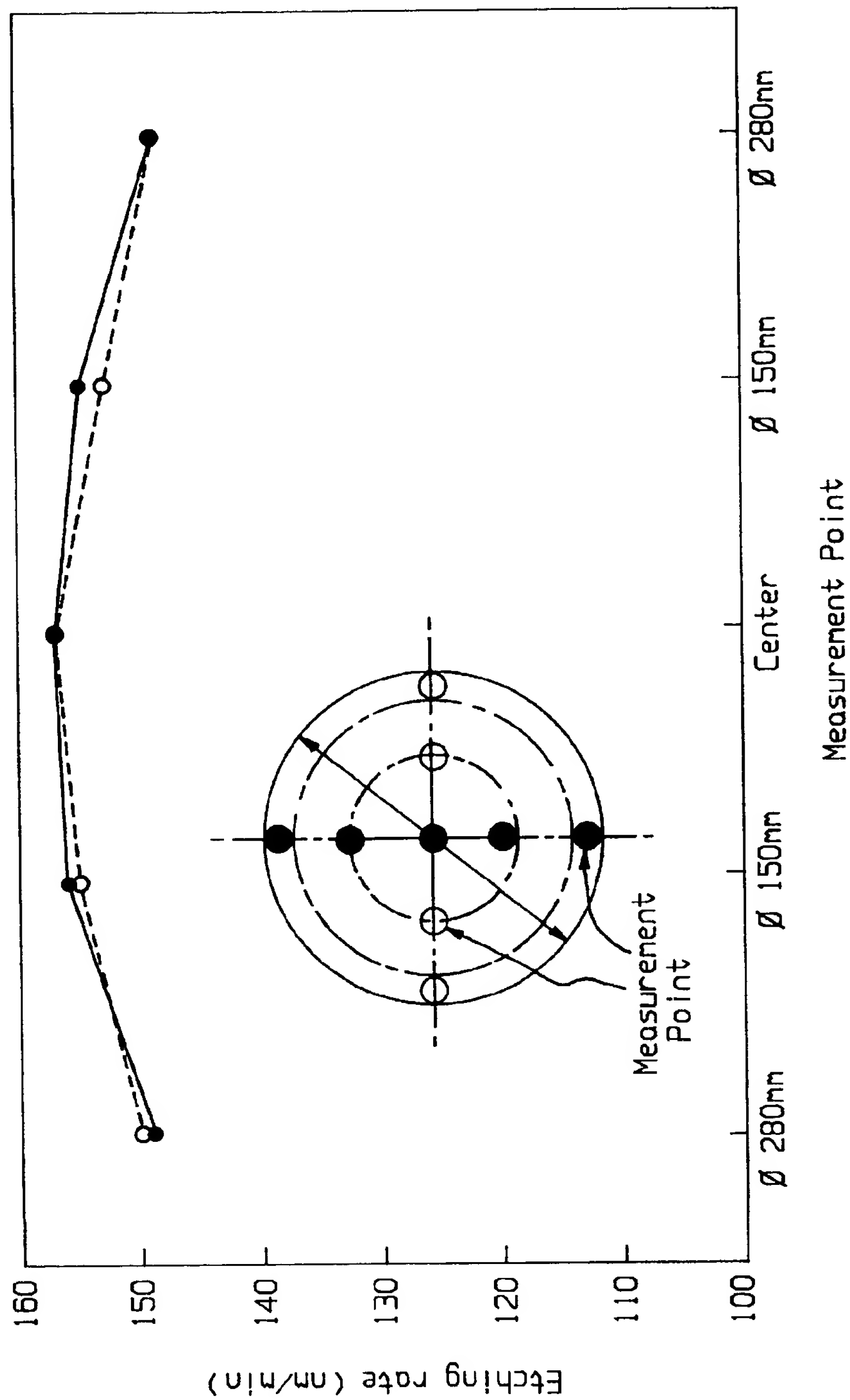


Fig. 35B



Etching rate (nm/min)
160
150
140
130
120
110
100
Ø 280mm
Ø 150mm
Center
Ø 150mm
Ø 280mm
Measurement Point
Measurement Point

Fig. 36

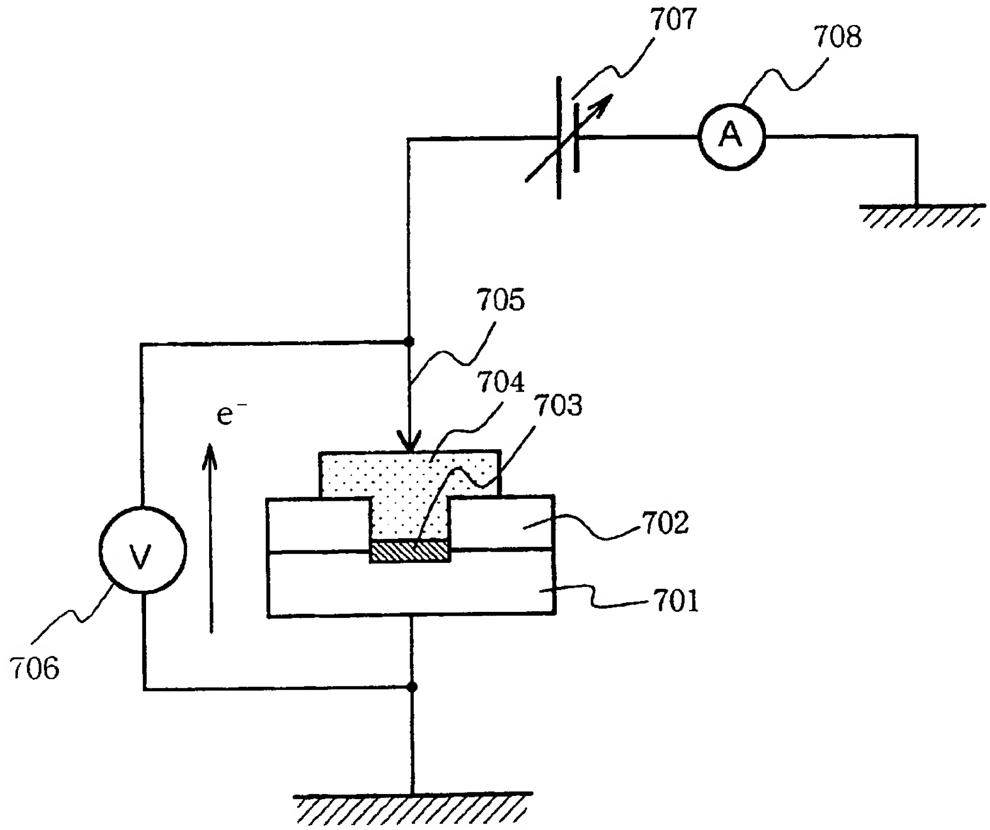


Fig. 37

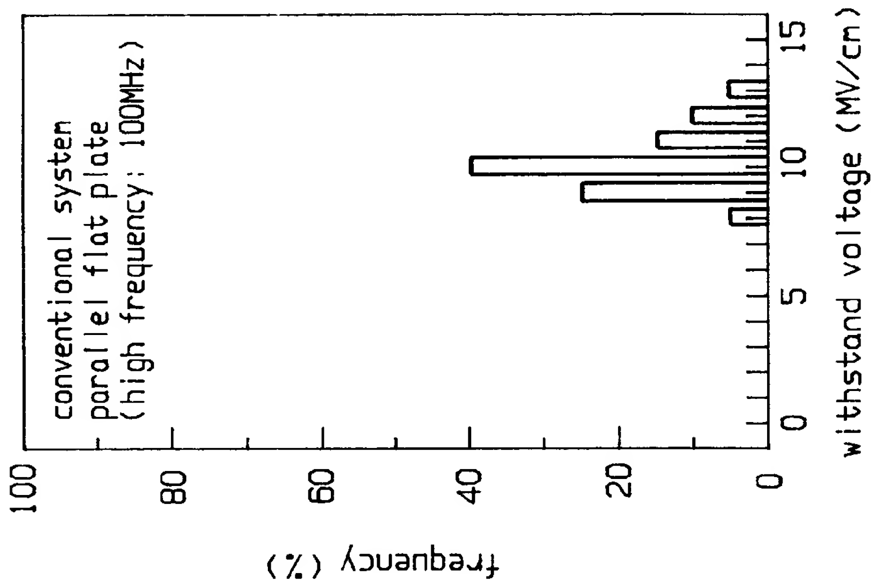


Fig. 38B

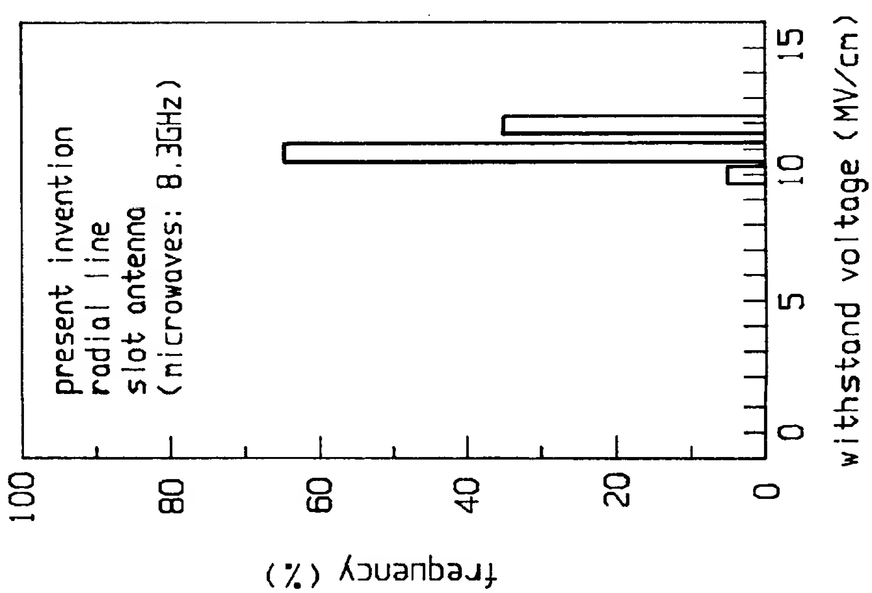


Fig. 38A

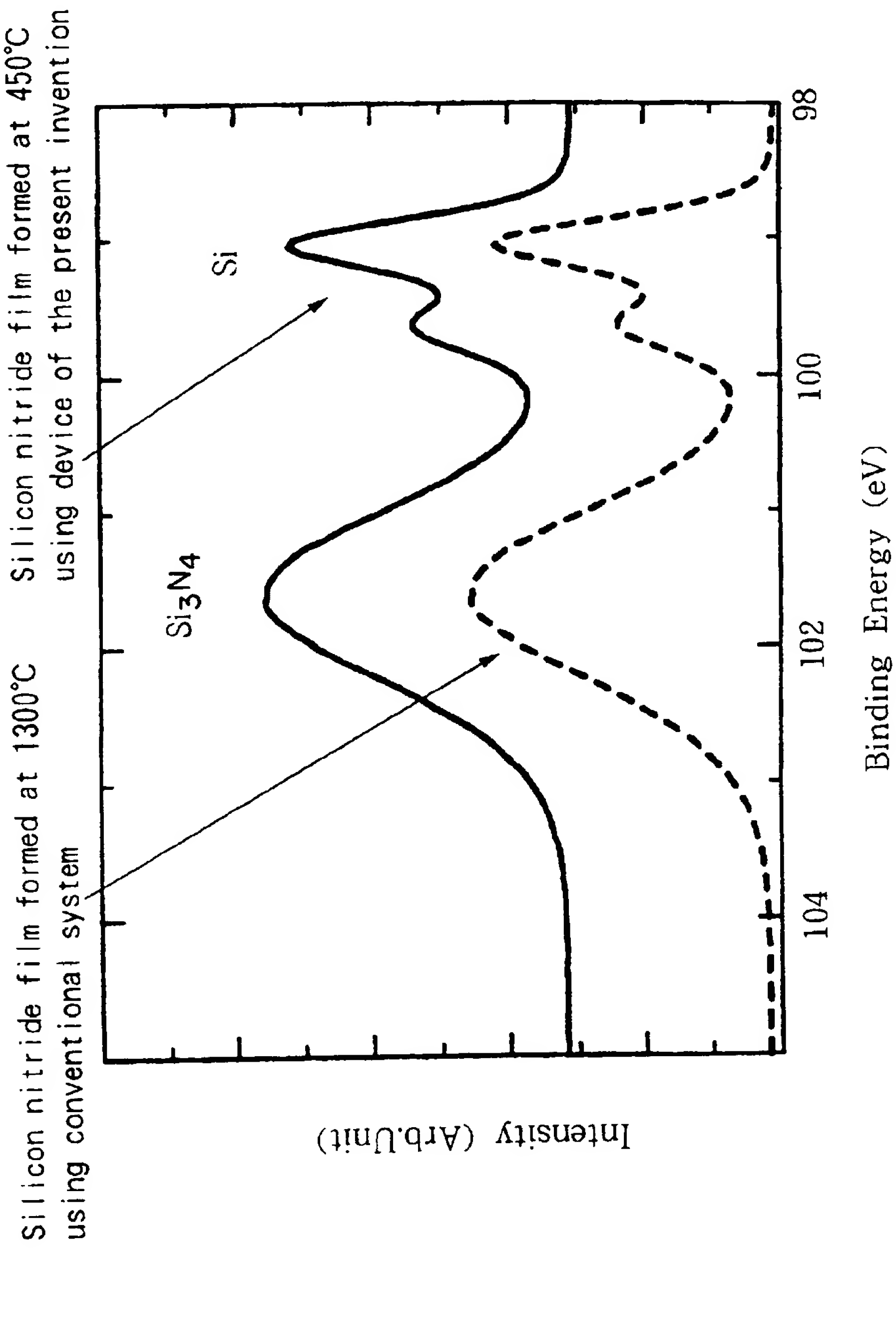

Silicon nitride film formed at 450°C
using device of the present invention
Silicon nitride film formed at 1300°C
using conventional system
Si
Si_3N_4
Intensity (Arb.Unit)
98
100
102
104
Binding Energy (eV)

Fig. 39

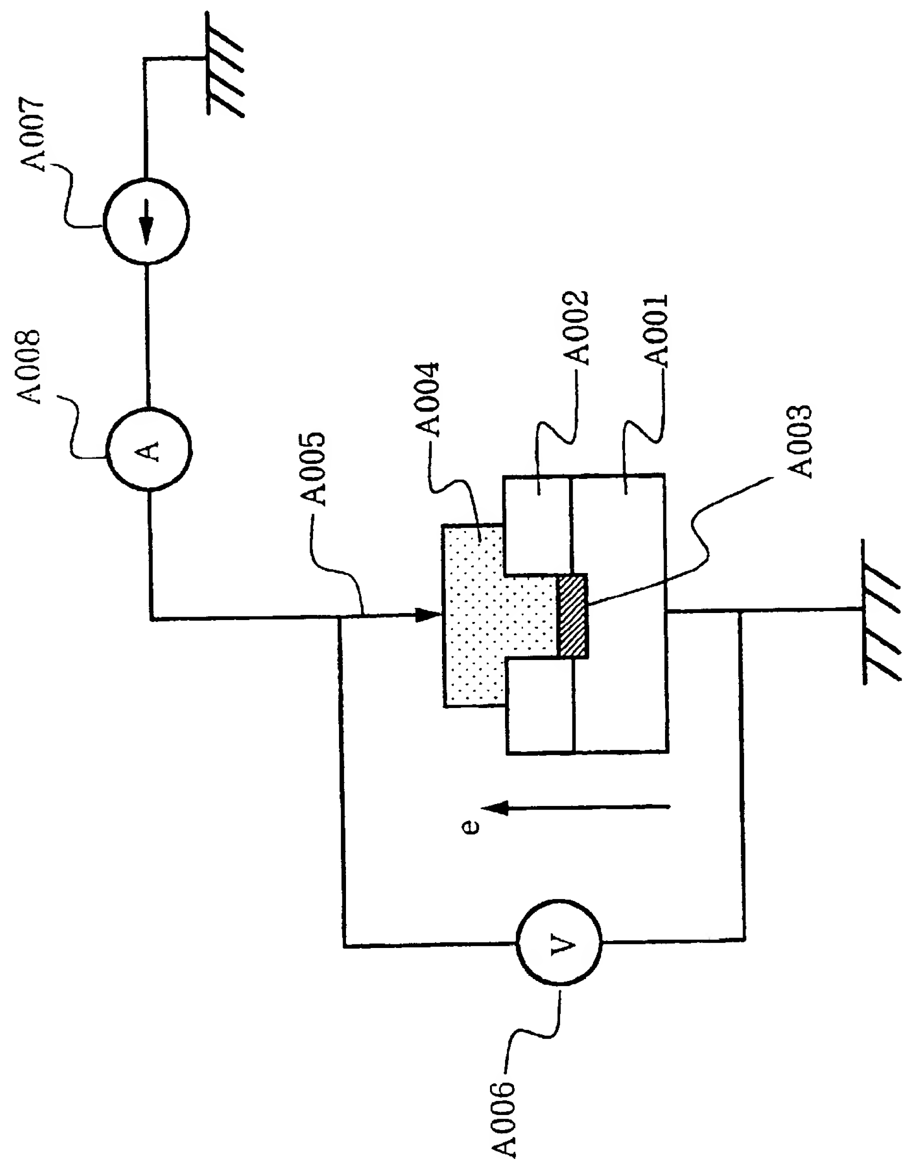
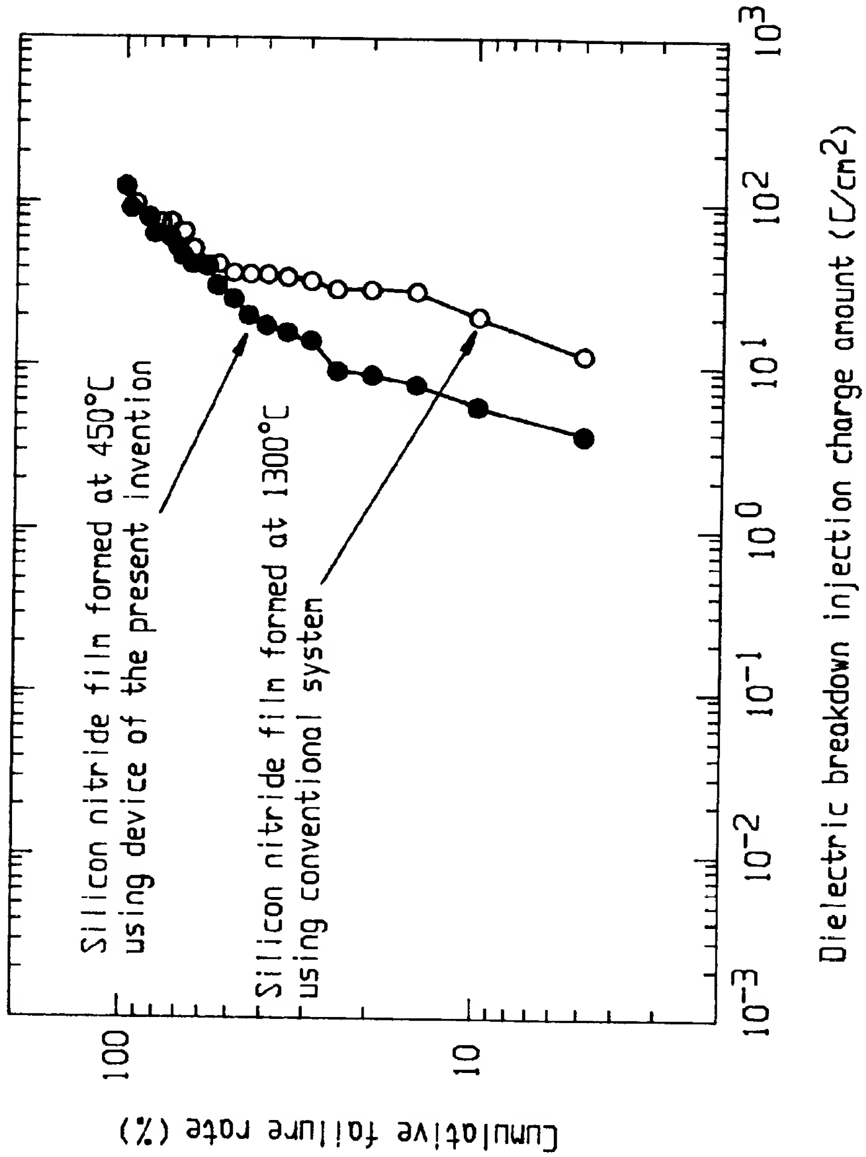


Fig. 40



Silicon nitride film formed at 450°C using device of the present invention
Silicon nitride film formed at 1300°C using conventional system
Cumulative failure rate (%)
100
10
Dielectric breakdown injection charge amount (C/cm²)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

Fig. 41

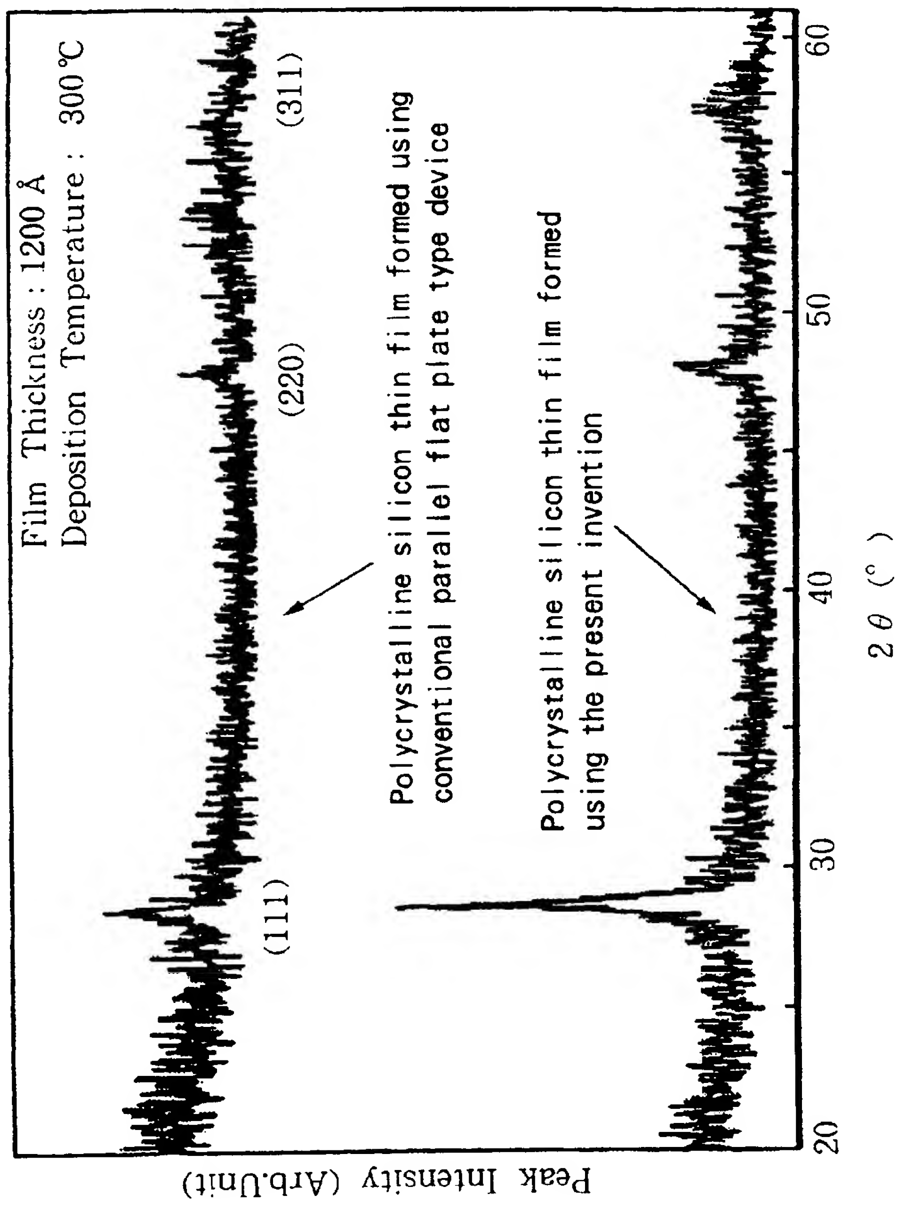
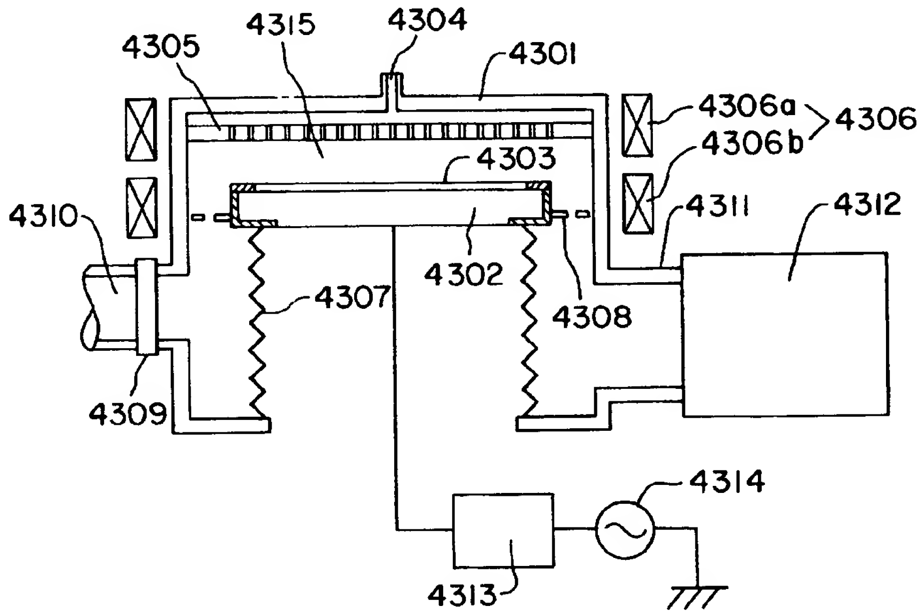
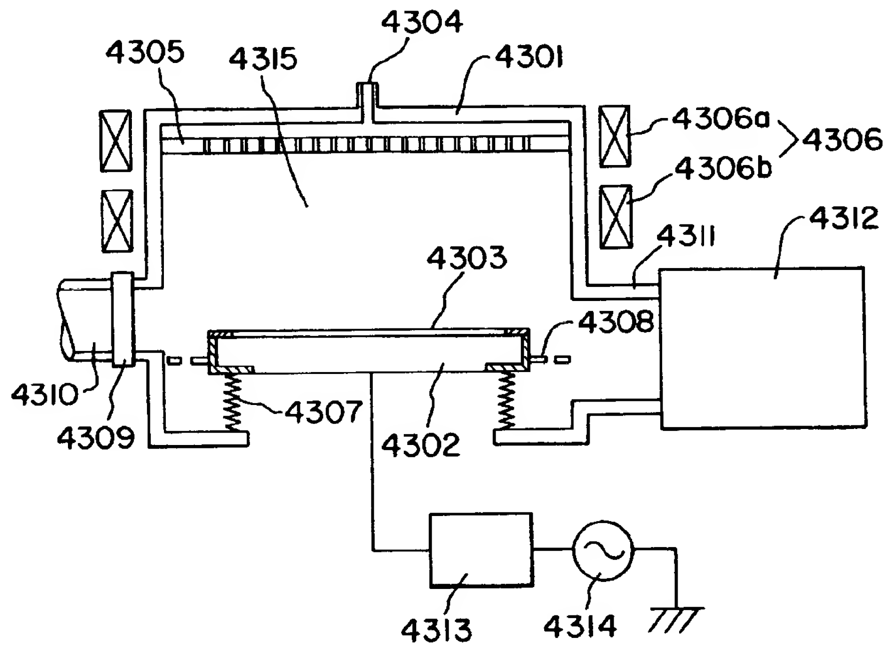

Film Thickness : 1200 Å
Deposition Temperature : 300 °C
(111)
(220)
(311)
Polycrystalline silicon thin film formed using conventional parallel flat plate type device
Polycrystalline silicon thin film formed using the present invention
20
30
40
50
60
2θ (°)
Peak Intensity (Arb.Unit)

Fig. 42



PRIOR ART

Fig. 43A



PRIOR ART

Fig. 43B

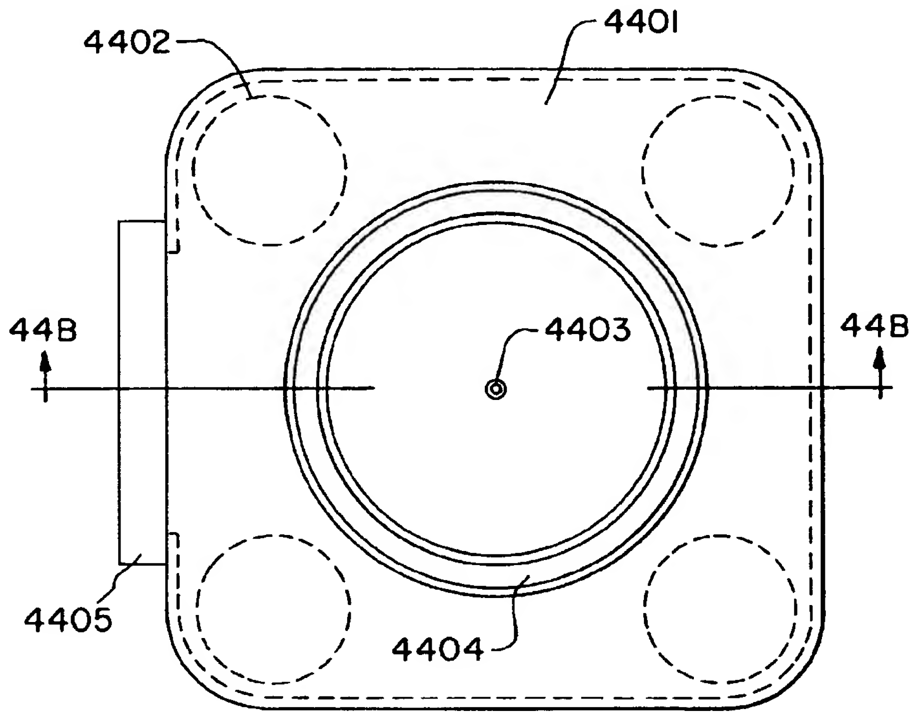


Fig. 44A

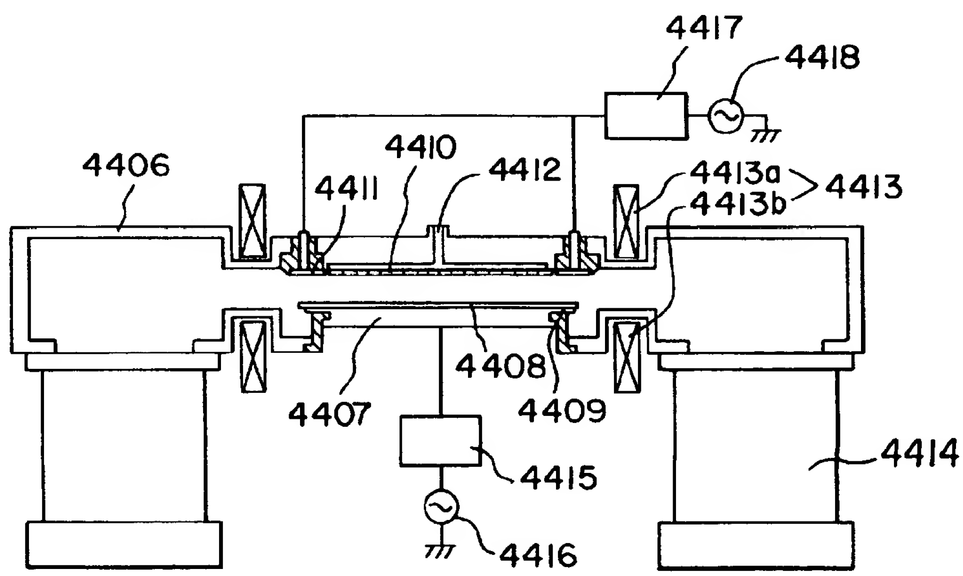


Fig. 44B

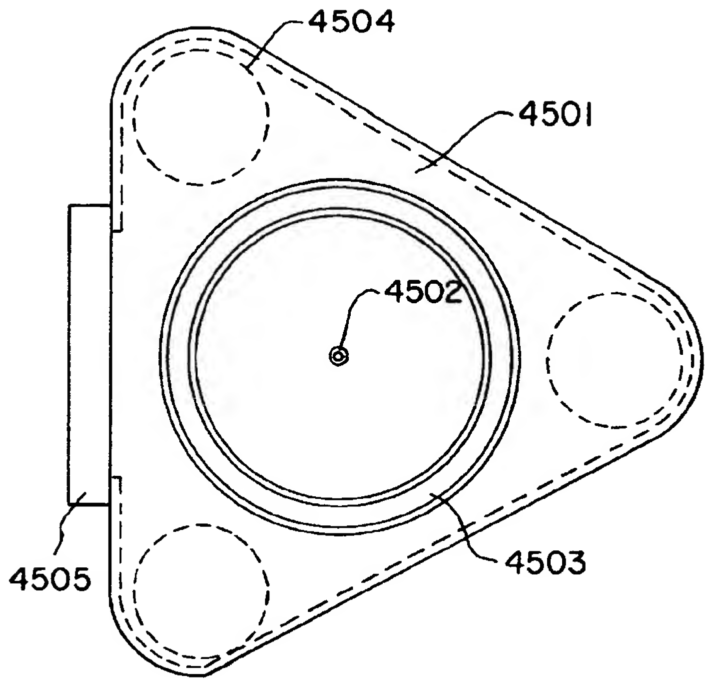


Fig. 45

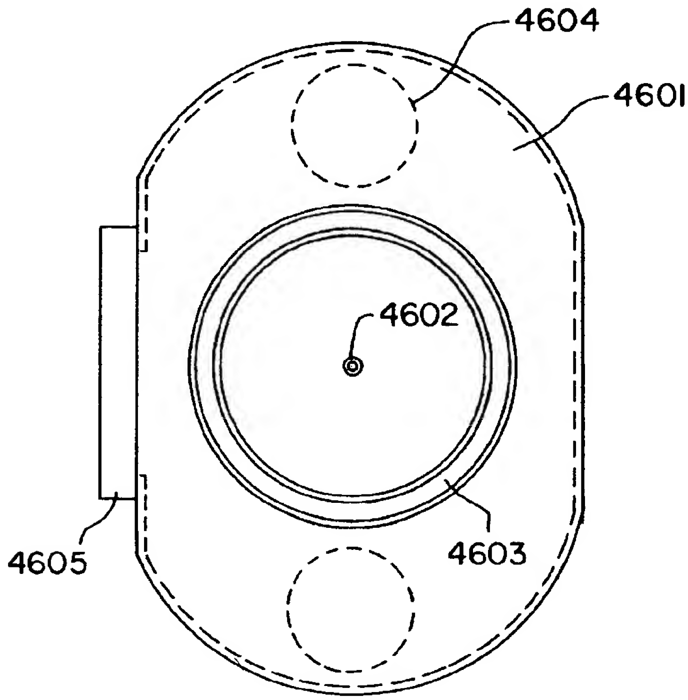


Fig. 46

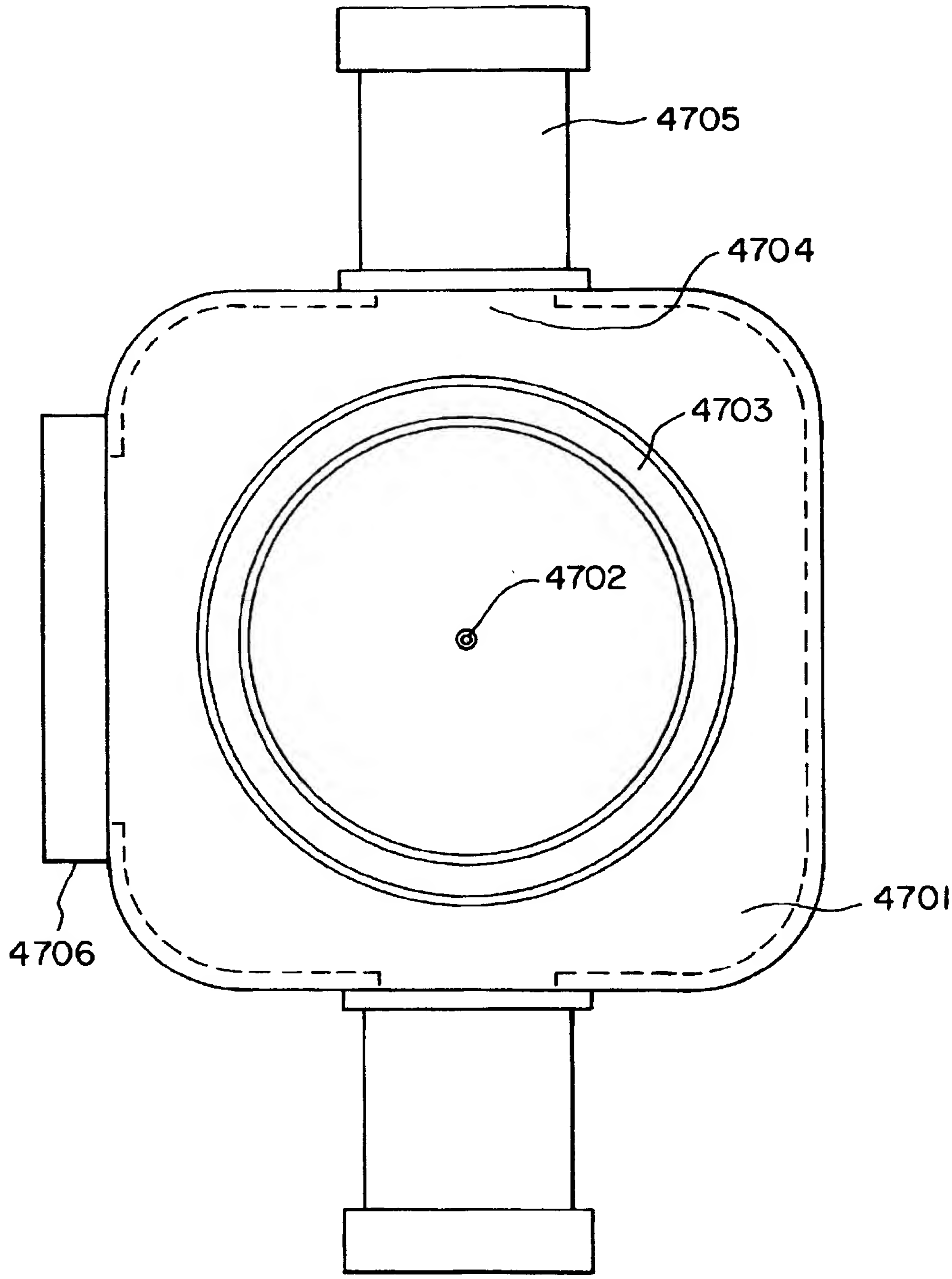


Fig. 47

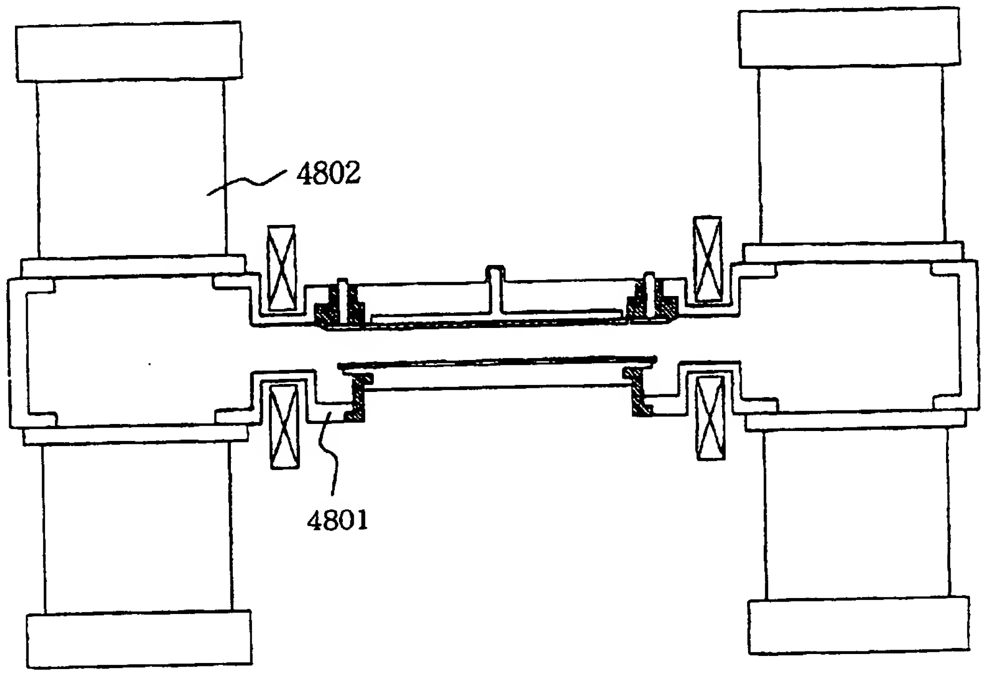


Fig. 48

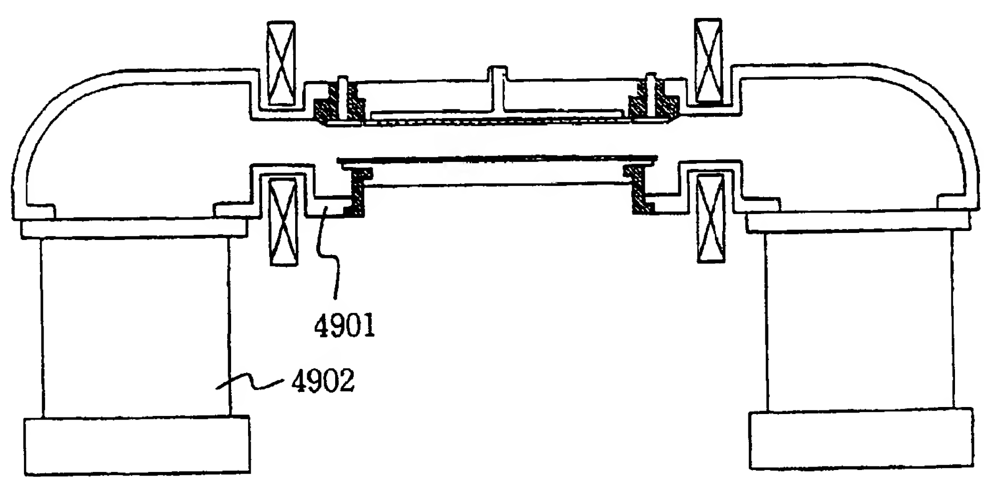


Fig. 49

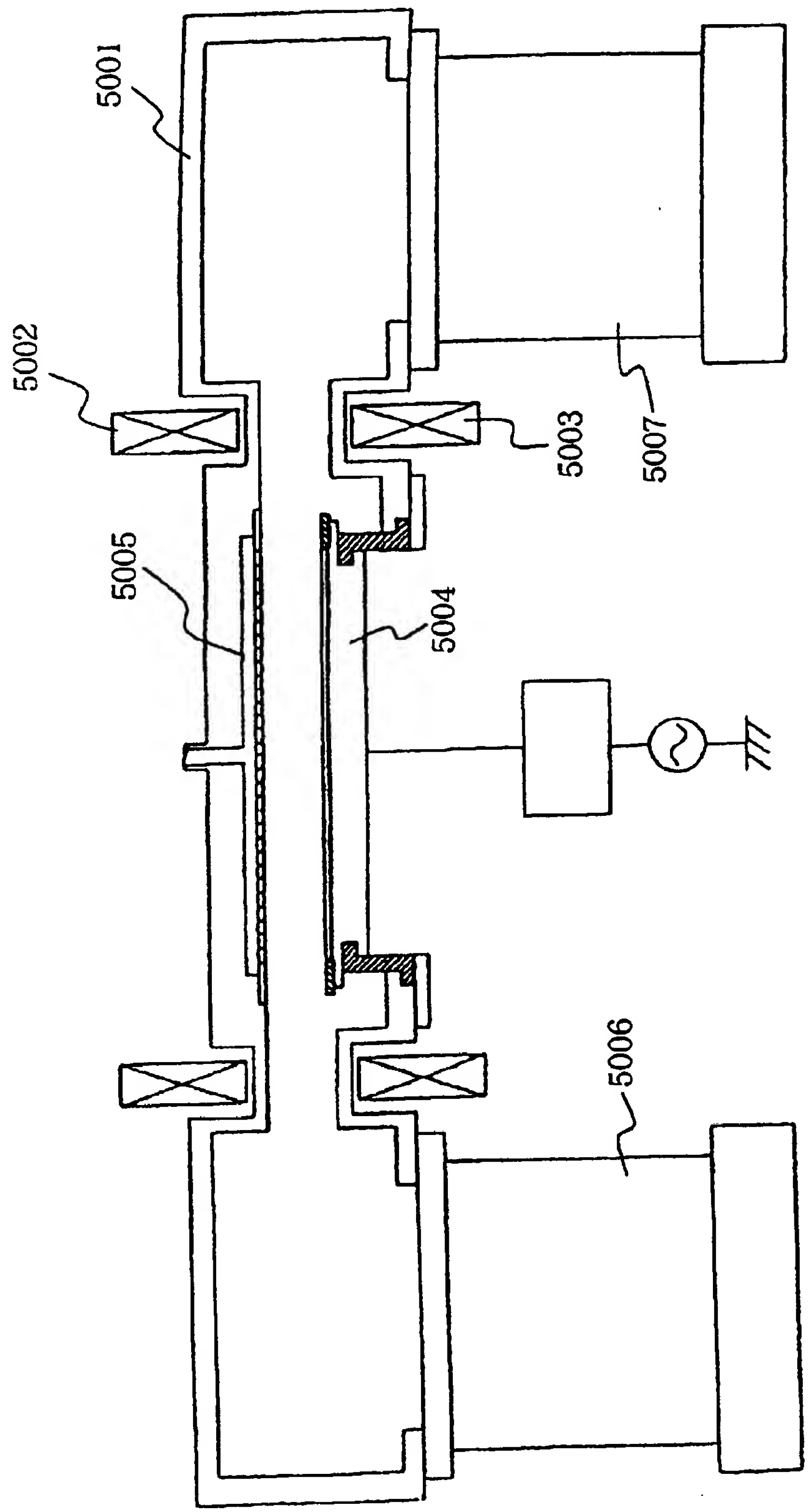


Fig. 50

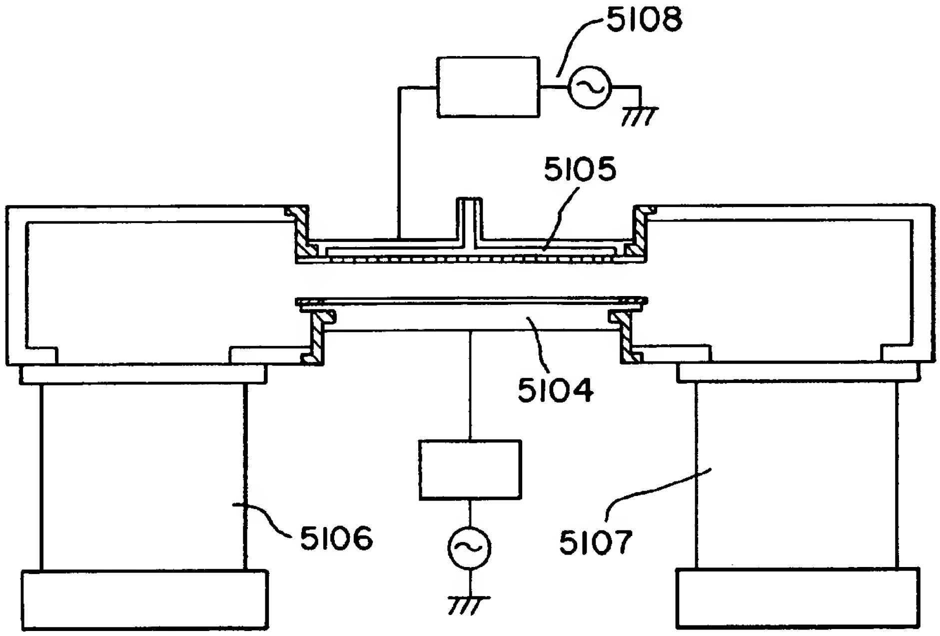


Fig. 51

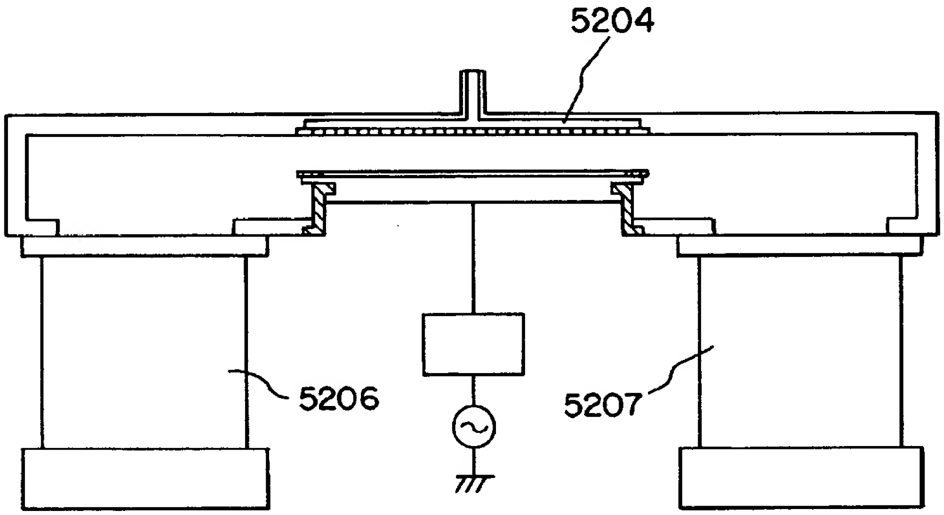


Fig. 52

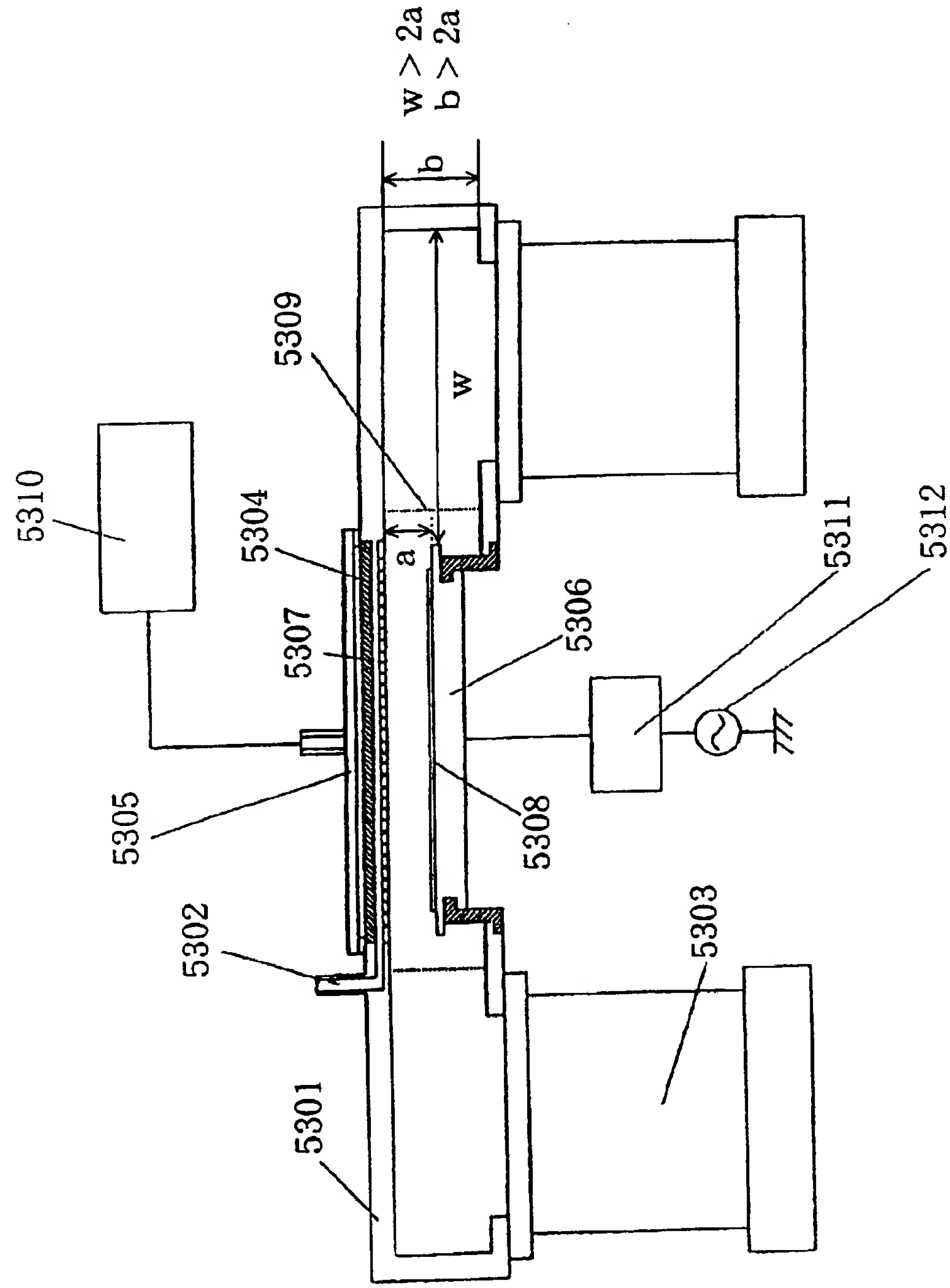

w > 2a
b > 2a
b
w
a
5301
5302
5303
5304
5305
5306
5307
5308
5309
5310
5311
5312

Fig. 53

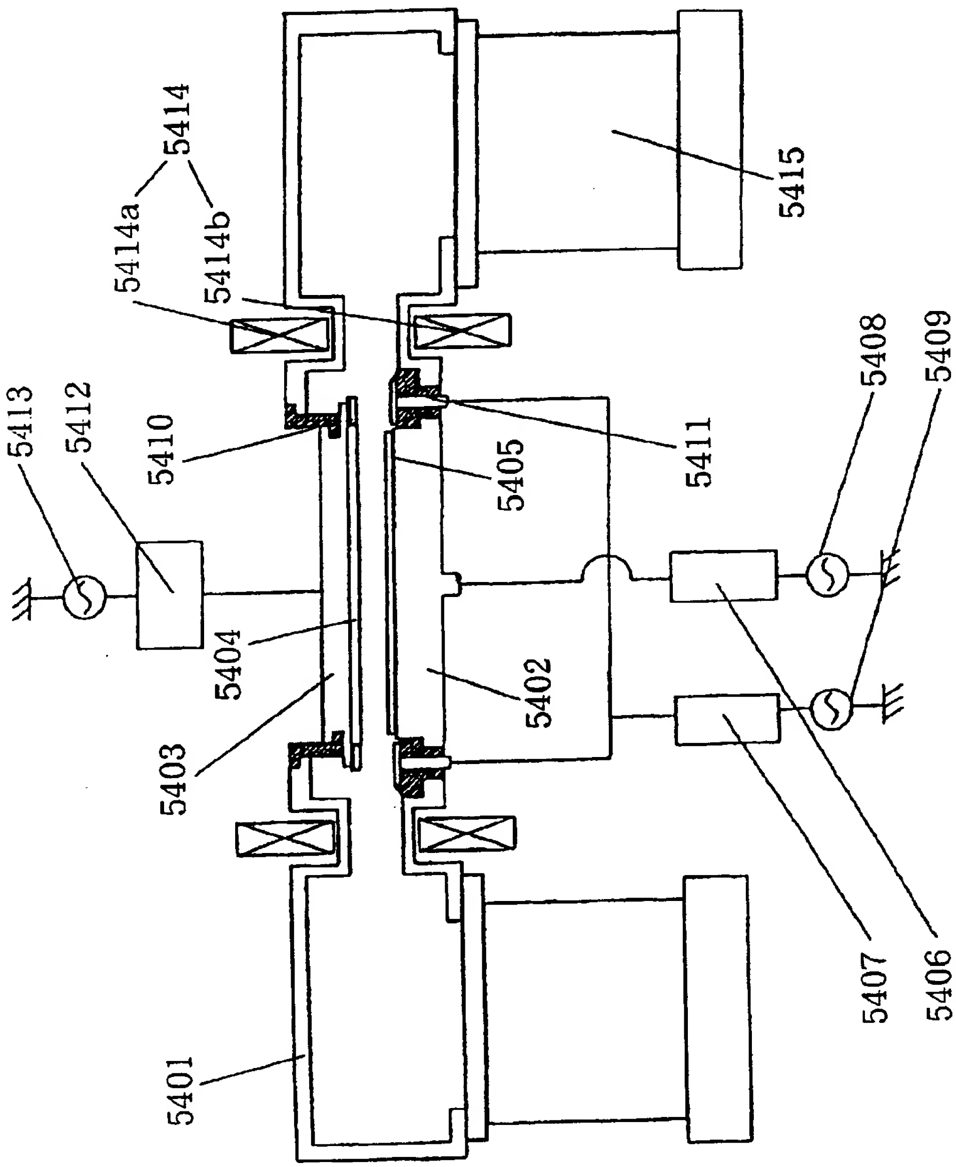

5401
5402
5403
5404
5405
5406
5407
5408
5409
5410
5411
5412
5413
5414
5414a
5414b
5415

Fig. 54

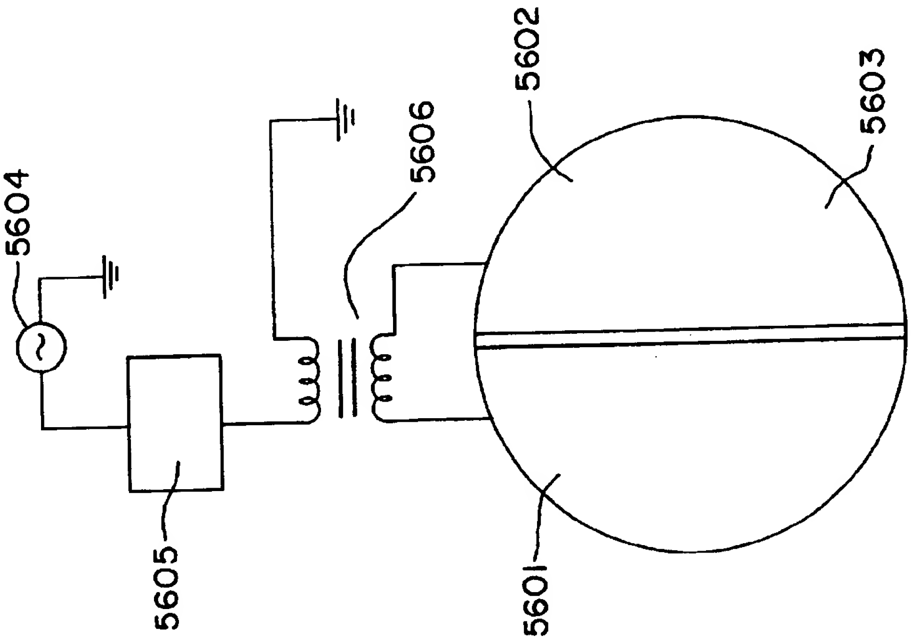

5601
5602
5603
5604
5605
5606

Fig. 56

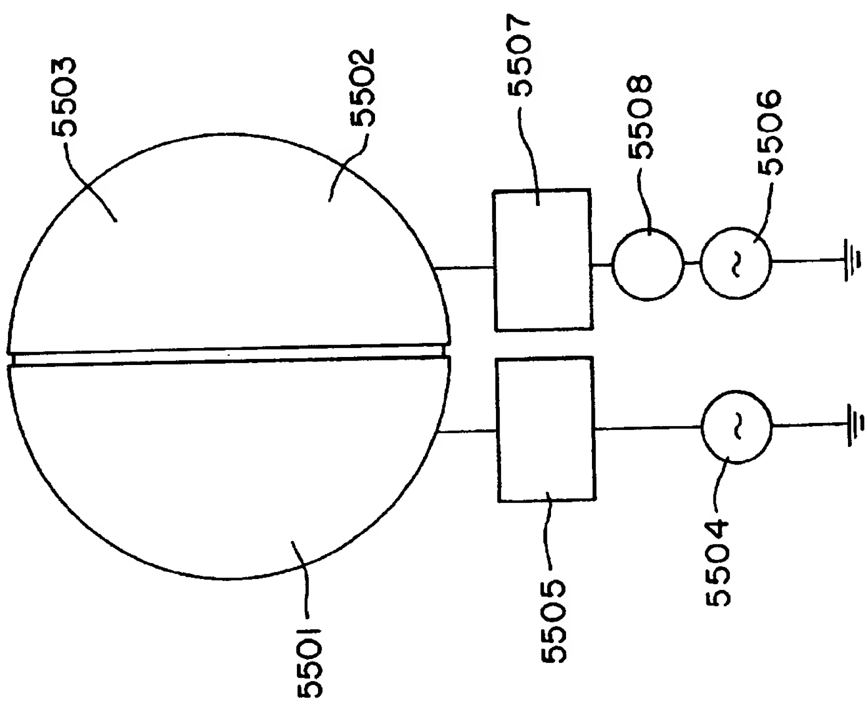
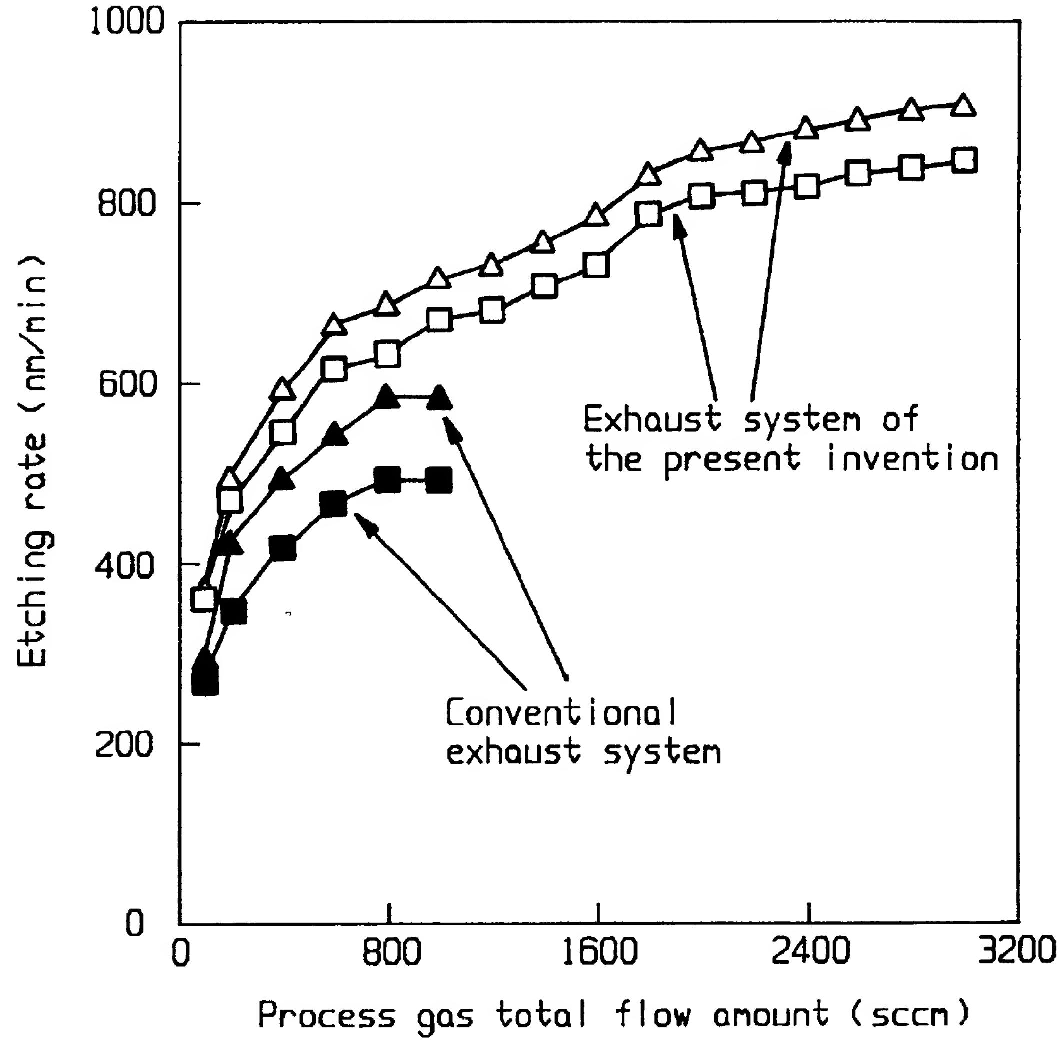

5501
5502
5503
5504
5505
5506
5507
5508

Fig. 55



1000
800
600
400
200
0
0
800
1600
2400
3200
Etching rate (nm/min)
Process gas total flow amount (sccm)
Exhaust system of the present invention
Conventional exhaust system

Fig. 57

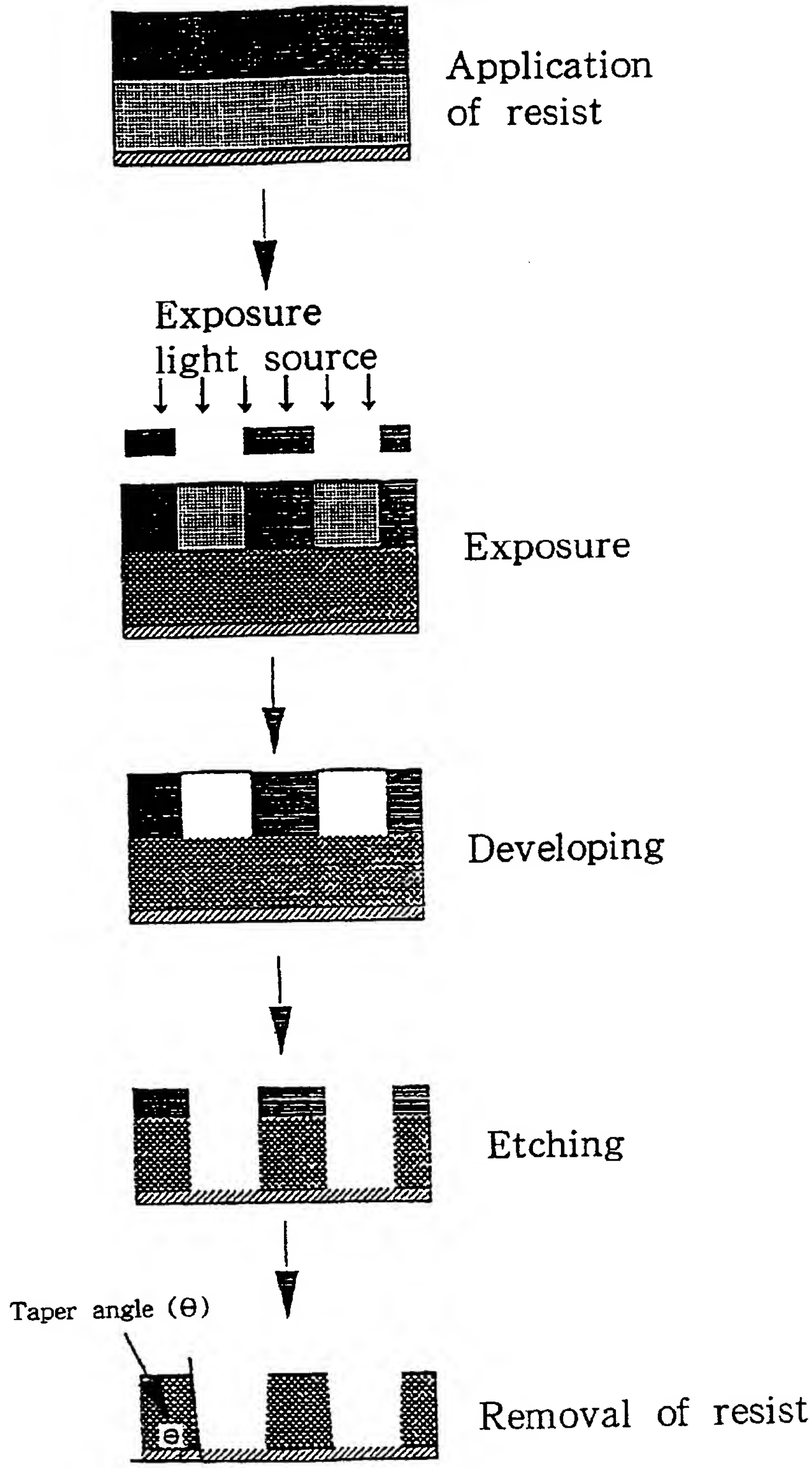

Application of resist
Exposure light source
Exposure
Developing
Etching
Taper angle (θ)
θ
Removal of resist

Fig. 58

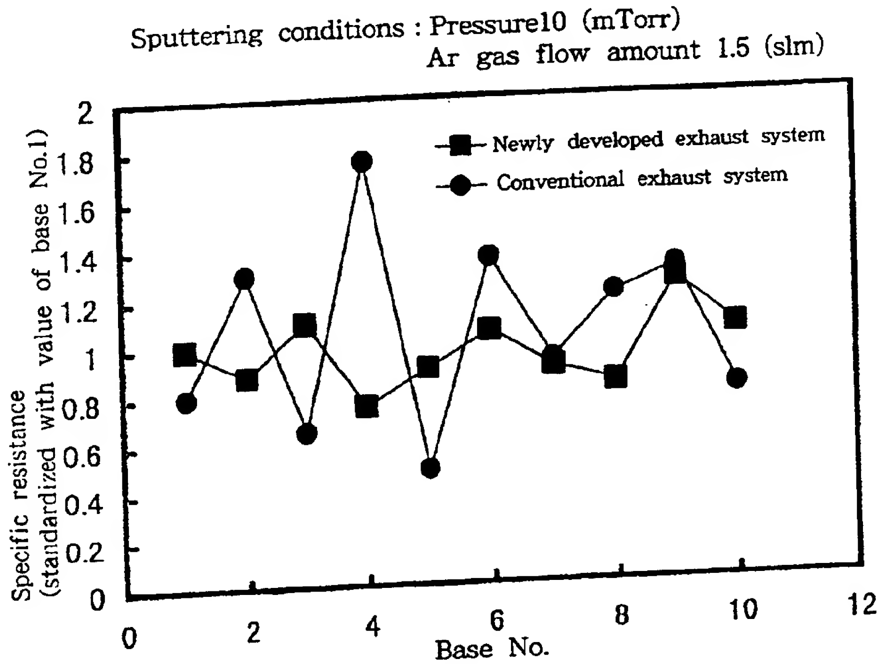

Sputtering conditions : Pressure10 (mTorr)
Ar gas flow amount 1.5 (slm)
Newly developed exhaust system
Conventional exhaust system
Specific resistance
(standardized with value of base No.1)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
Base No.

Fig. 59

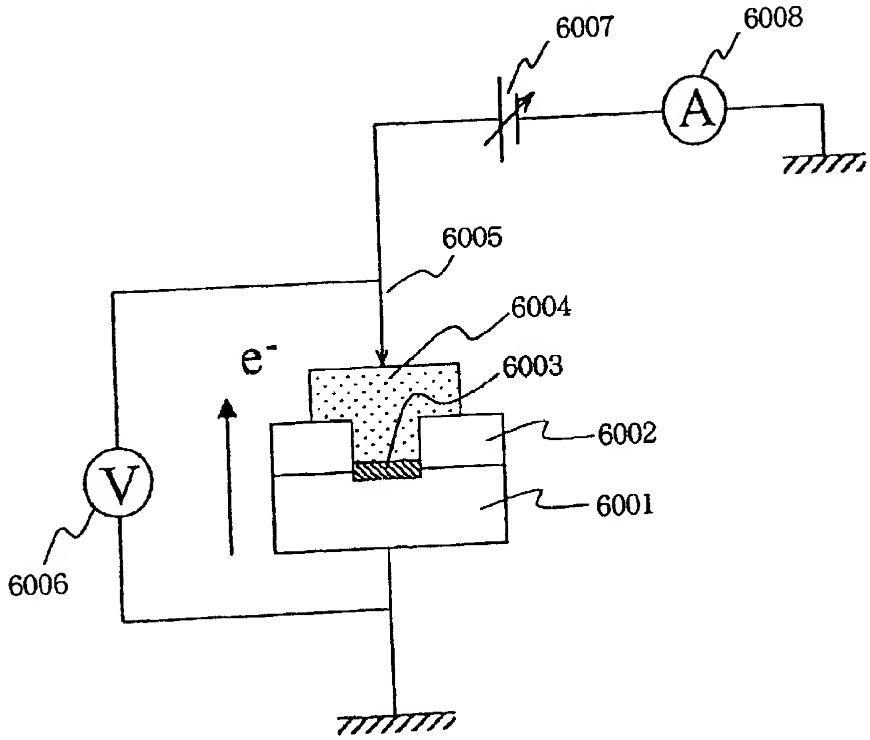

6007
6008
A
6005
6004
e⁻
6003
6002
6001
V
6006

Fig. 60

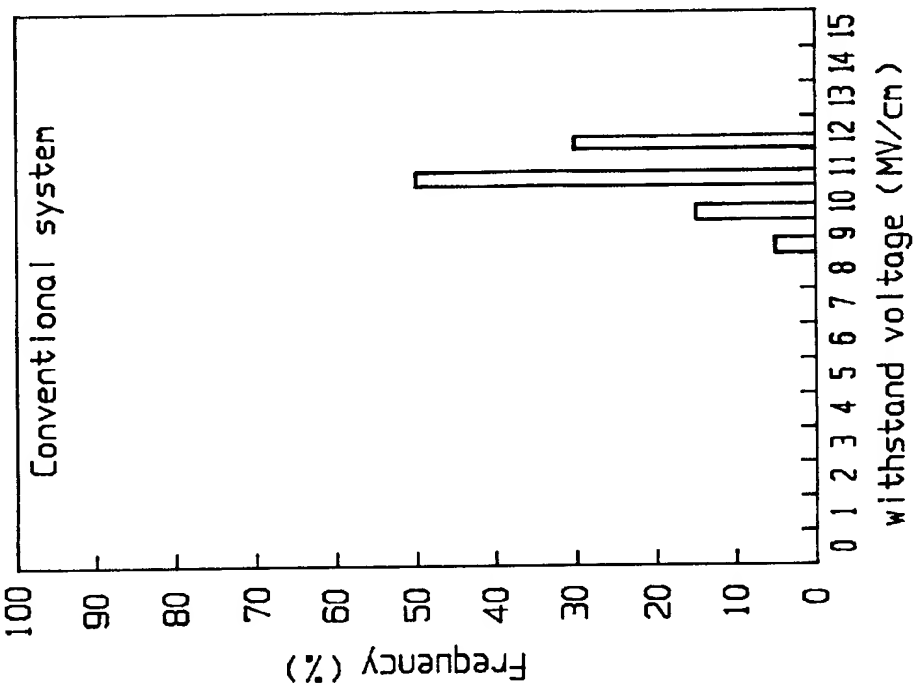


Fig. 61B

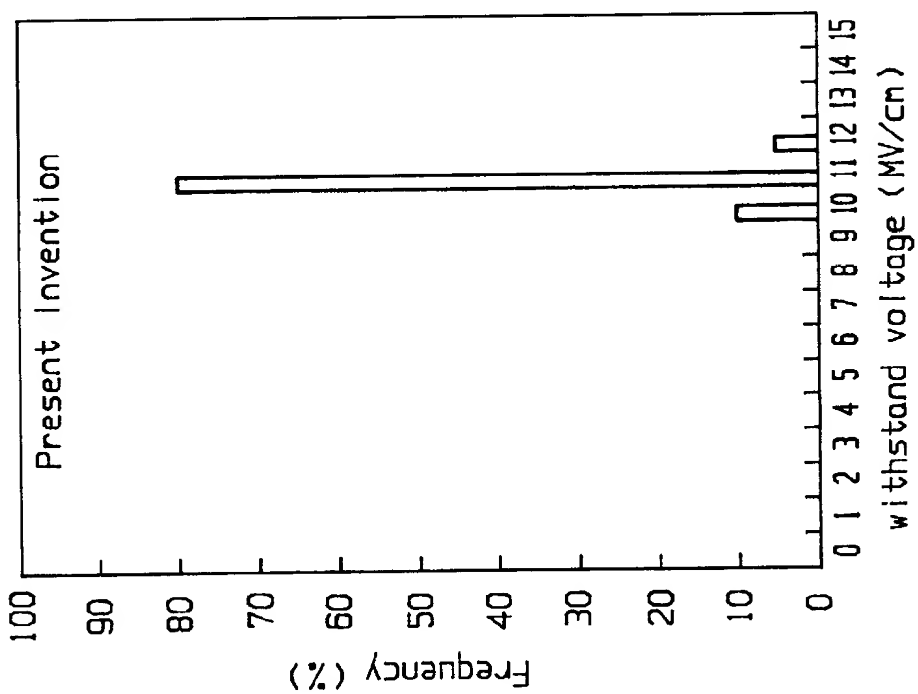


Fig. 61A

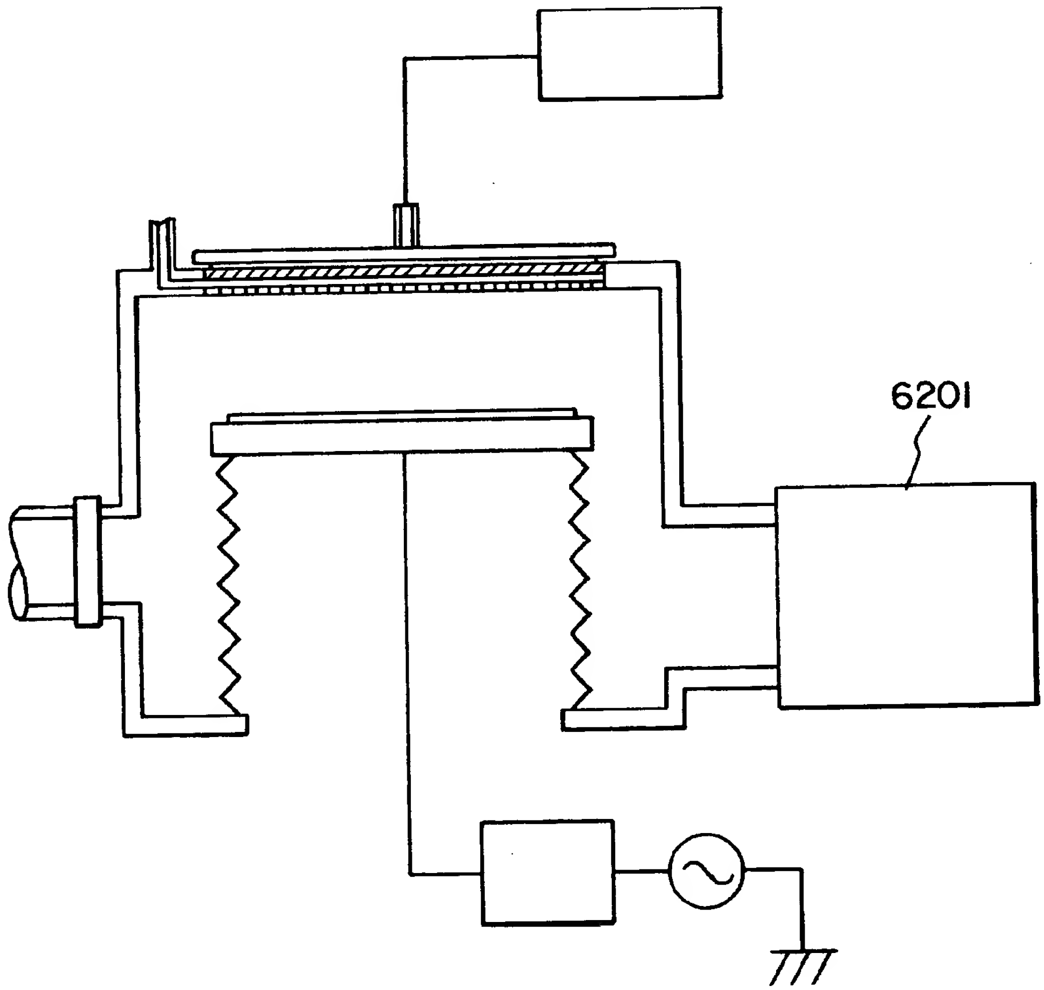


Fig. 62

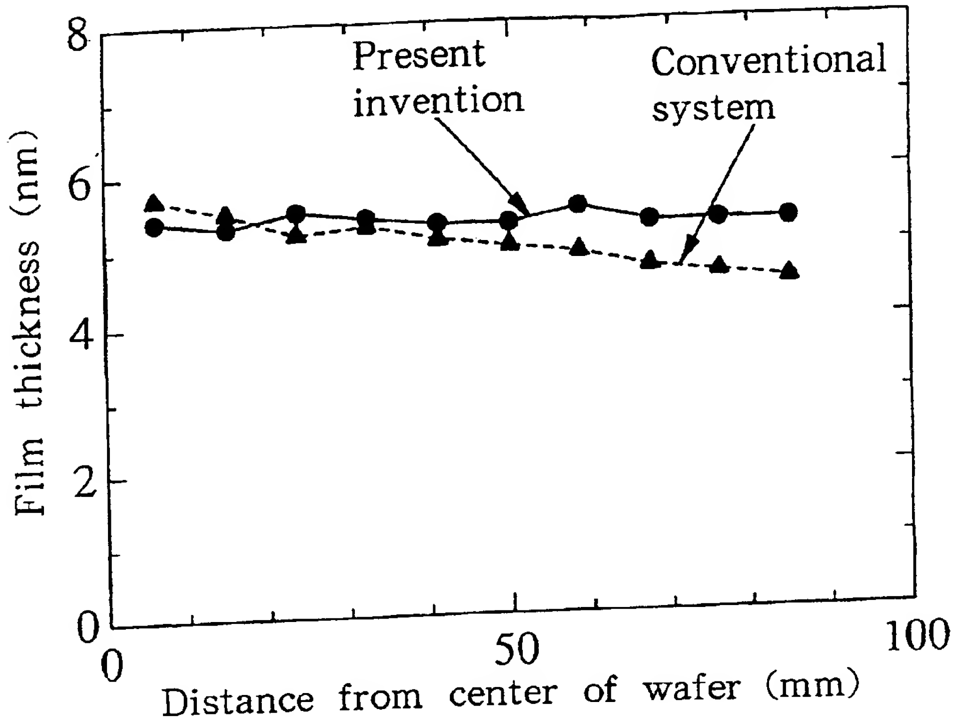

Present invention
Conventional system
Film thickness (nm)
Distance from center of wafer (mm)
0
2
4
6
8
0
50
100

Fig. 63

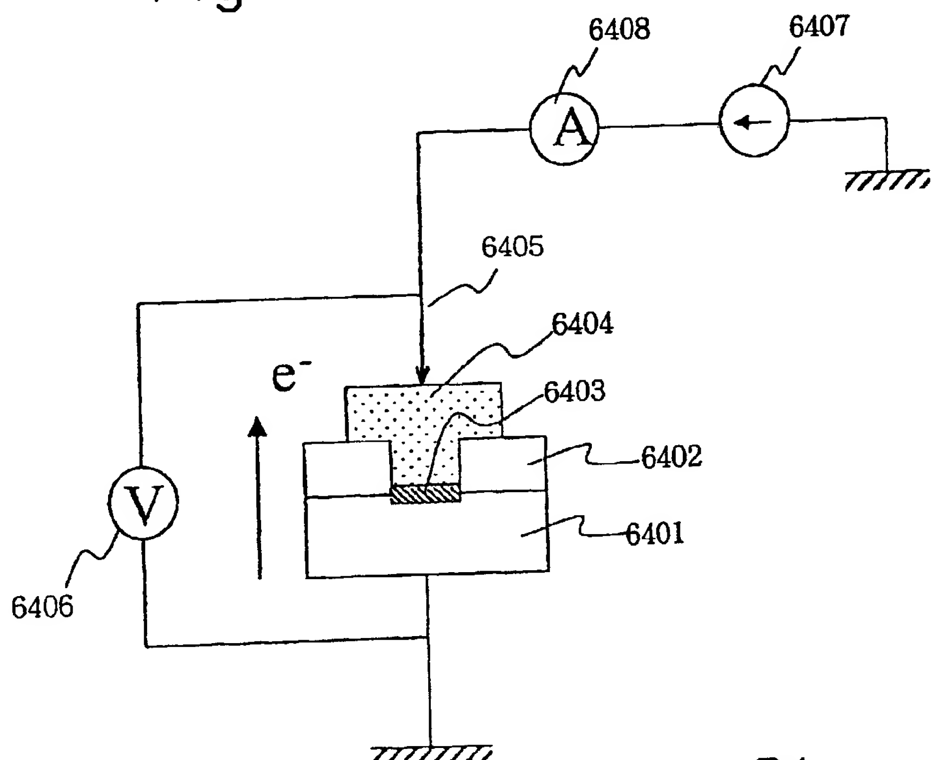
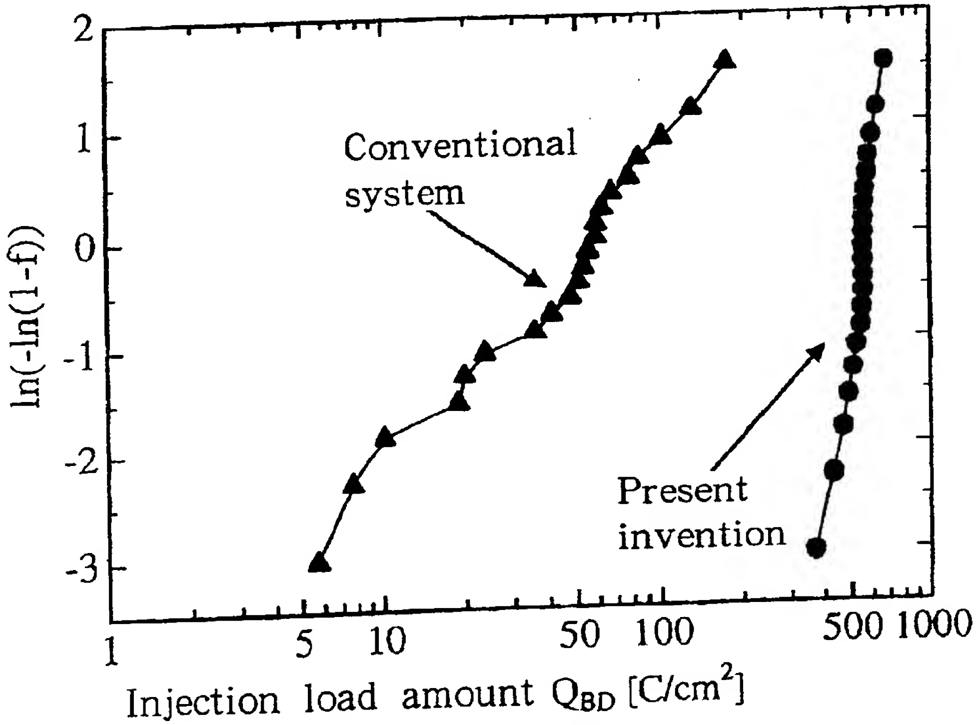
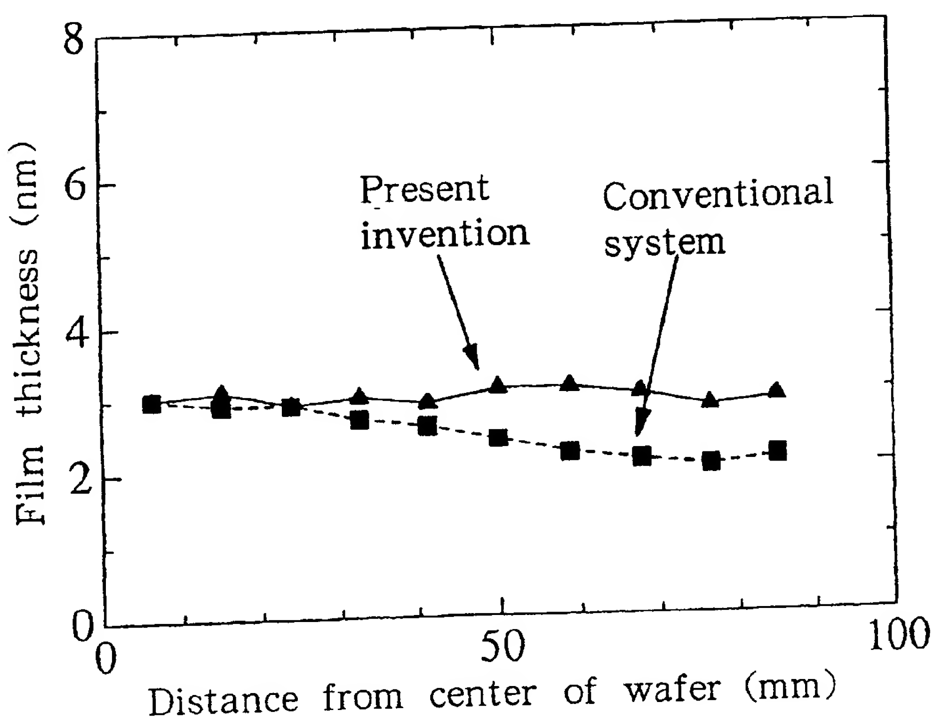

6408
6407
A
6405
6404
e⁻
6403
6402
6401
V
6406

Fig. 64



2
1
0
-1
-2
-3
ln(-ln(1-f))
Conventional system
Present invention
1
5
10
50
100
500
1000
Injection load amount Q_{BD} [C/cm^2]

Fig. 65



8
6
4
2
0
Film thickness (nm)
Present invention
Conventional system
0
50
100
Distance from center of wafer (mm)

Fig. 66

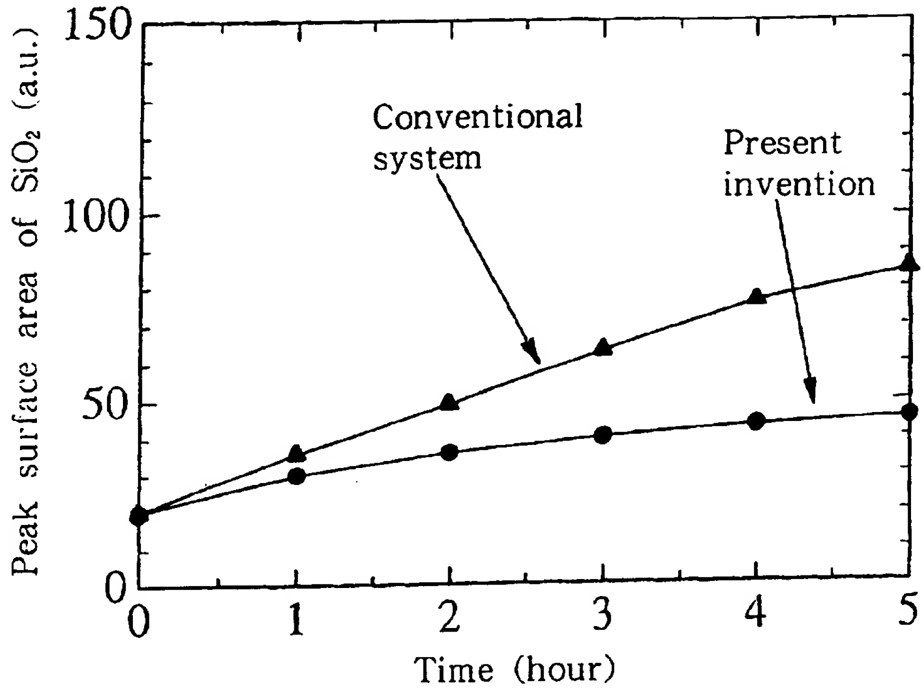

Peak surface area of SiO_2 (a.u.)
150
100
50
0
Conventional system
Present invention
0
1
2
3
4
5
Time (hour)

Fig. 67

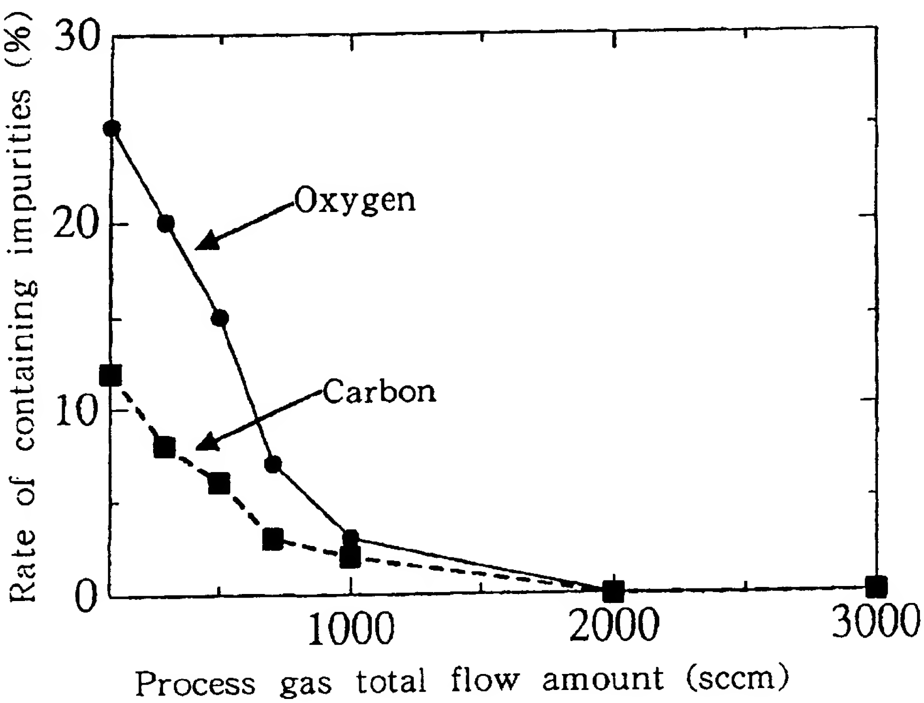

Rate of containing impurities (%)
30
20
10
0
Oxygen
Carbon
1000
2000
3000
Process gas total flow amount (sccm)

Fig. 68

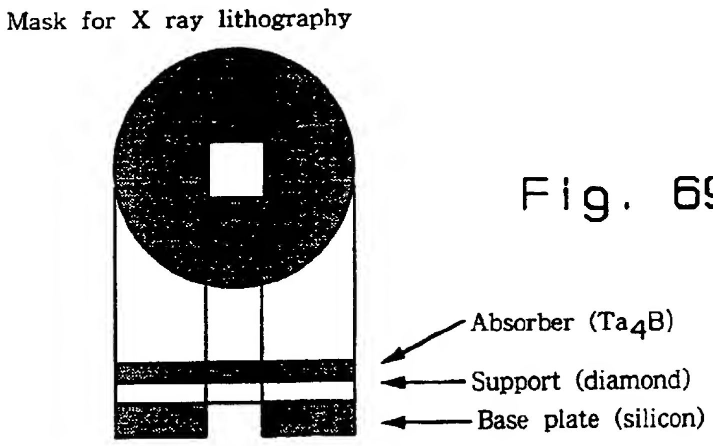


Fig. 69

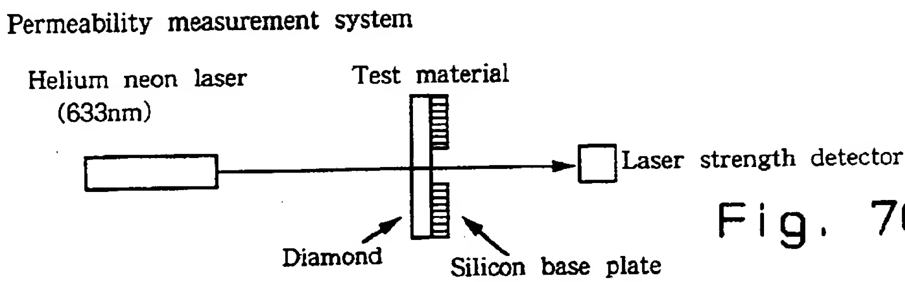


Fig. 70

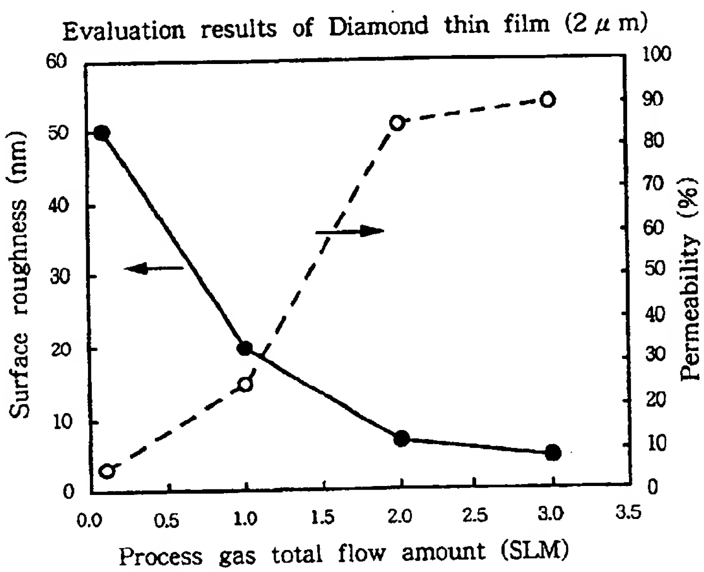


Fig. 71

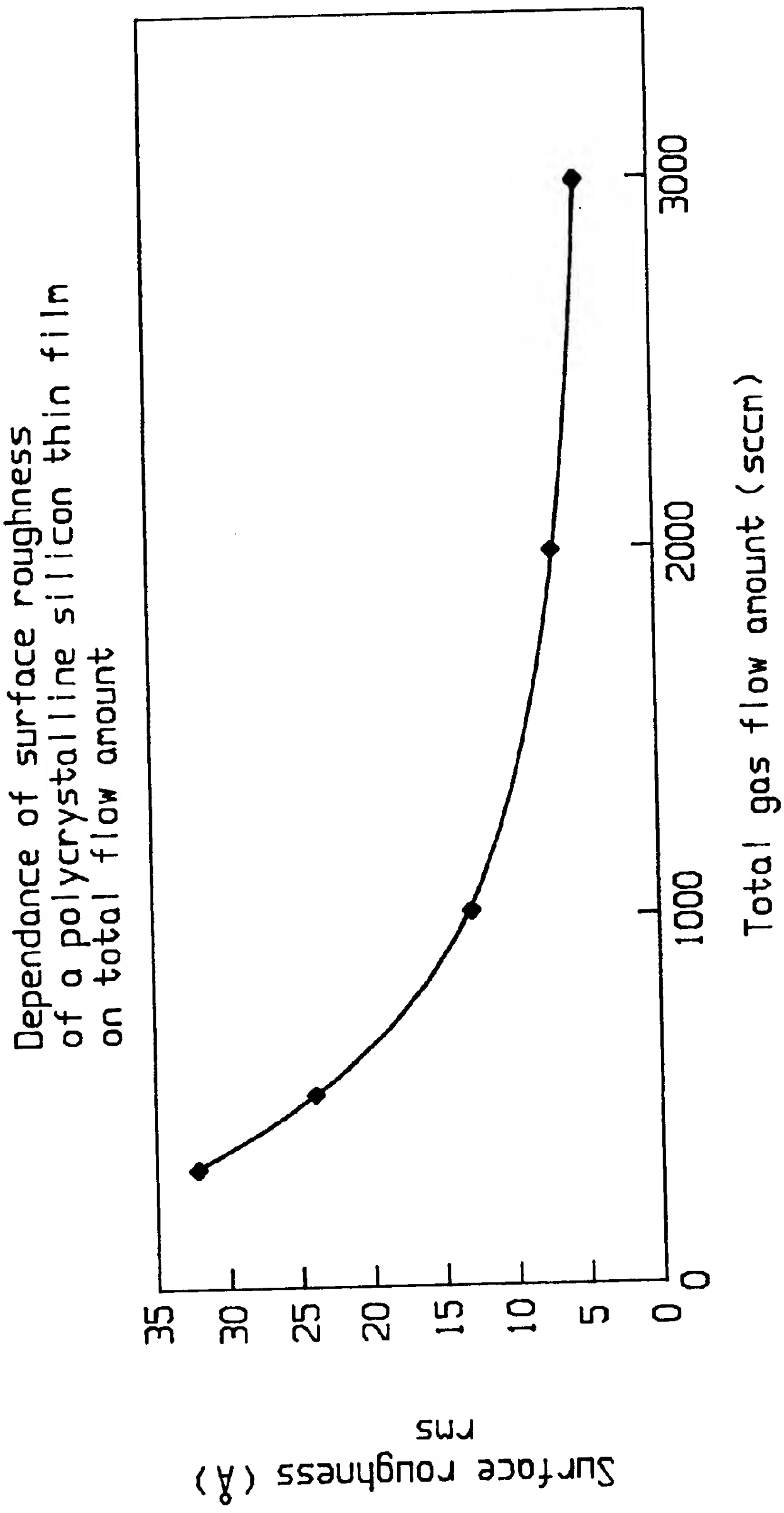

Dependance of surface roughness
of a polycrystalline silicon thin film
on total flow amount
Surface roughness (Å)
rms
35
30
25
20
15
10
5
0
0
1000
2000
3000
Total gas flow amount (sccm)

Fig. 72

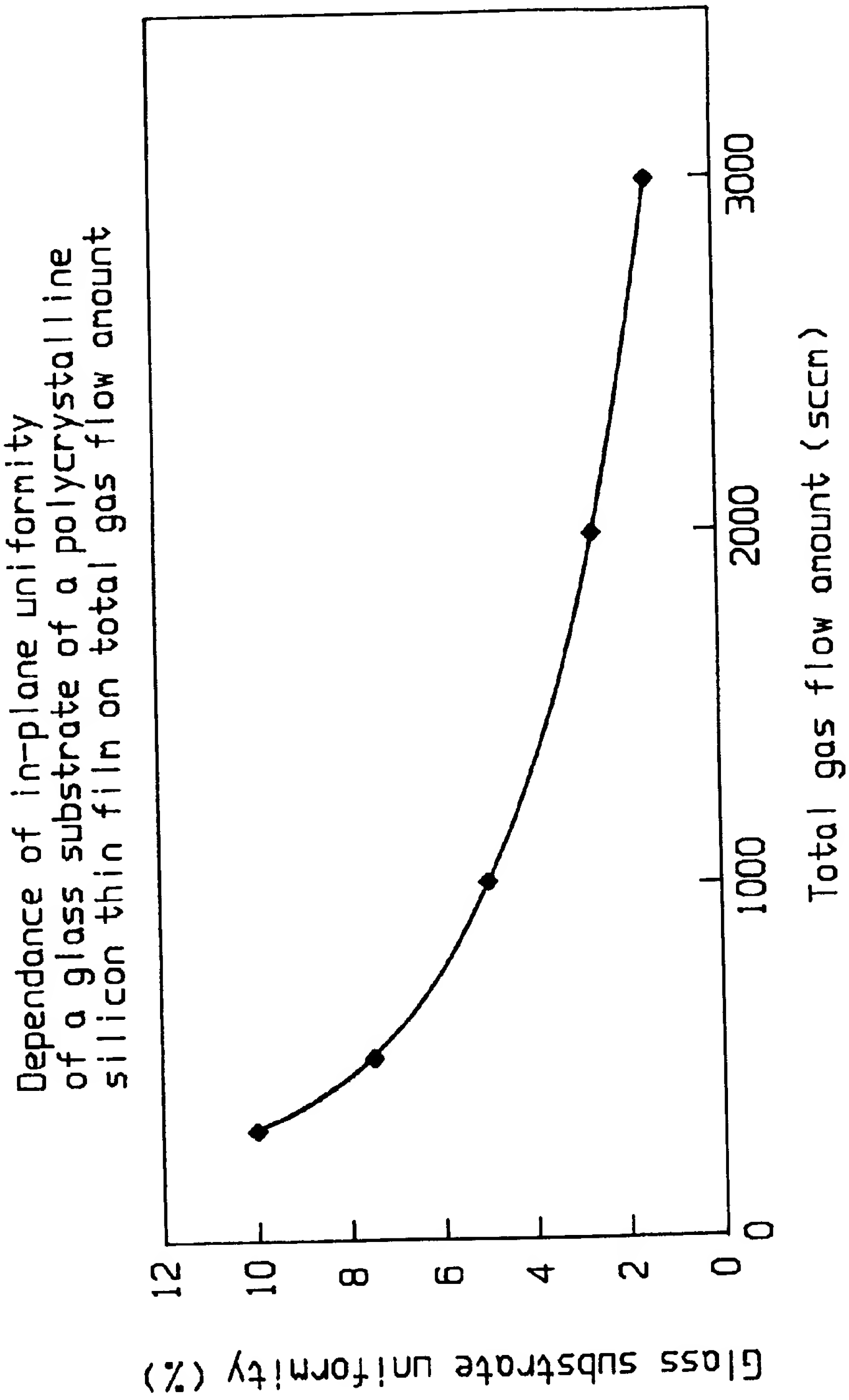

Dependance of in-plane uniformity
of a glass substrate of a polycrystalline
silicon thin film on total gas flow amount
Glass substrate uniformity (%)
0
2
4
6
8
10
12
0
1000
2000
3000
Total gas flow amount (sccm)

Fig. 73

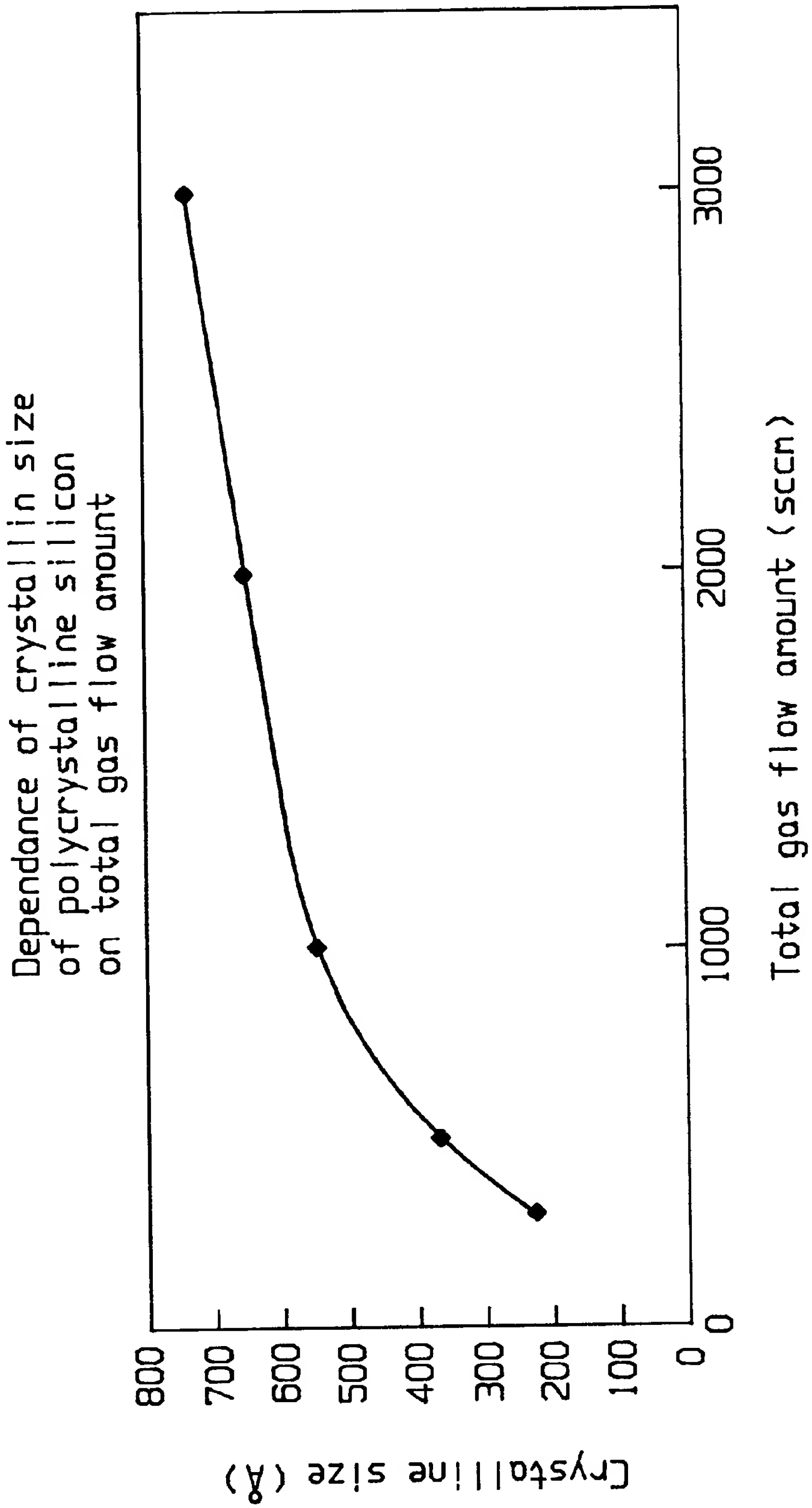

Dependance of crystallin size
of polycrystalline silicon
on total gas flow amount
Total gas flow amount (sccm)
Crystalline size (Å)
0
1000
2000
3000
0
100
200
300
400
500
600
700
800

Fig. 74

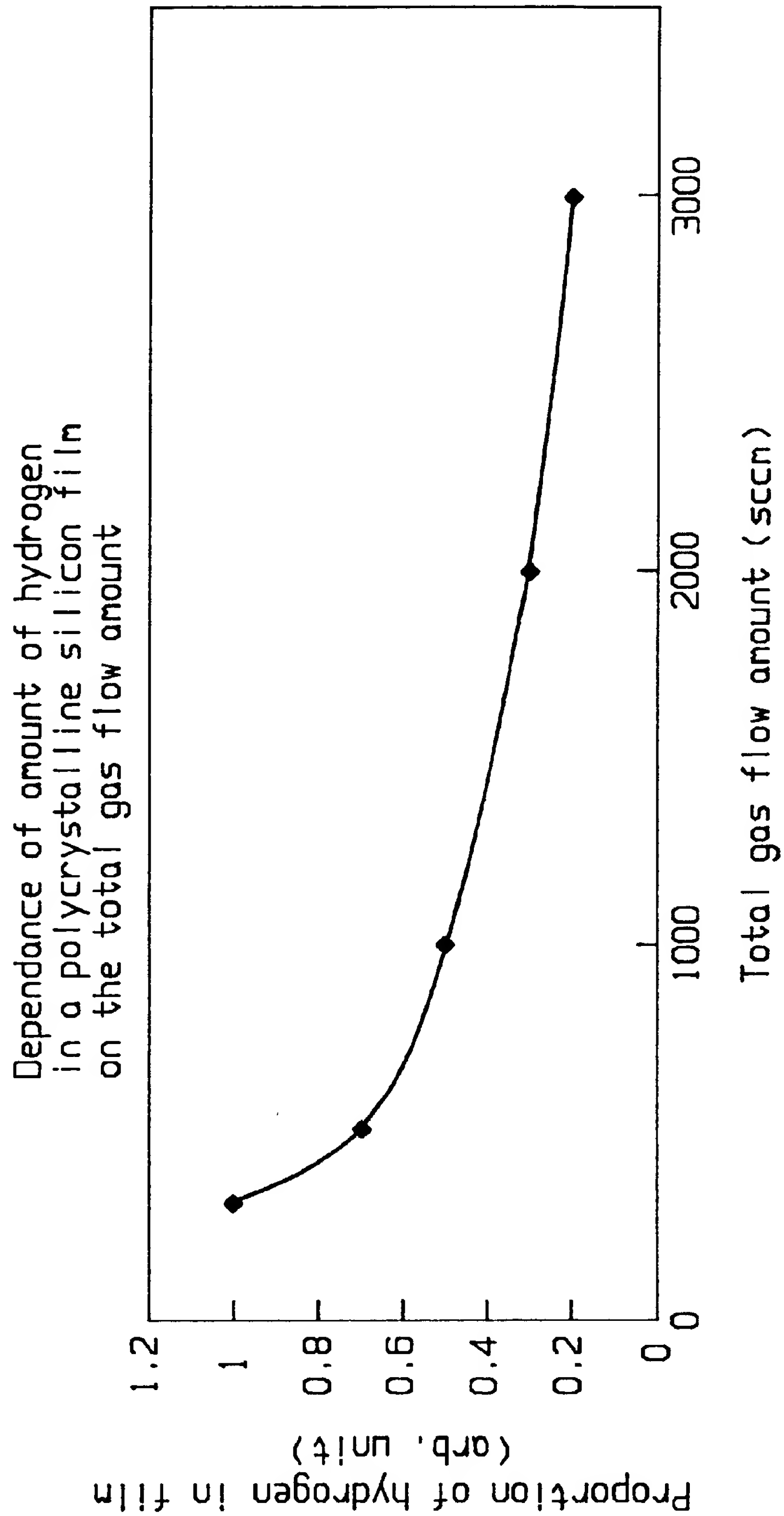

Dependance of amount of hydrogen
in a polycrystalline silicon film
on the total gas flow amount
Proportion of hydrogen in film
(arb. unit)
1.2
1
0.8
0.6
0.4
0.2
0
0
1000
2000
3000
Total gas flow amount (sccm)

Fig. 75

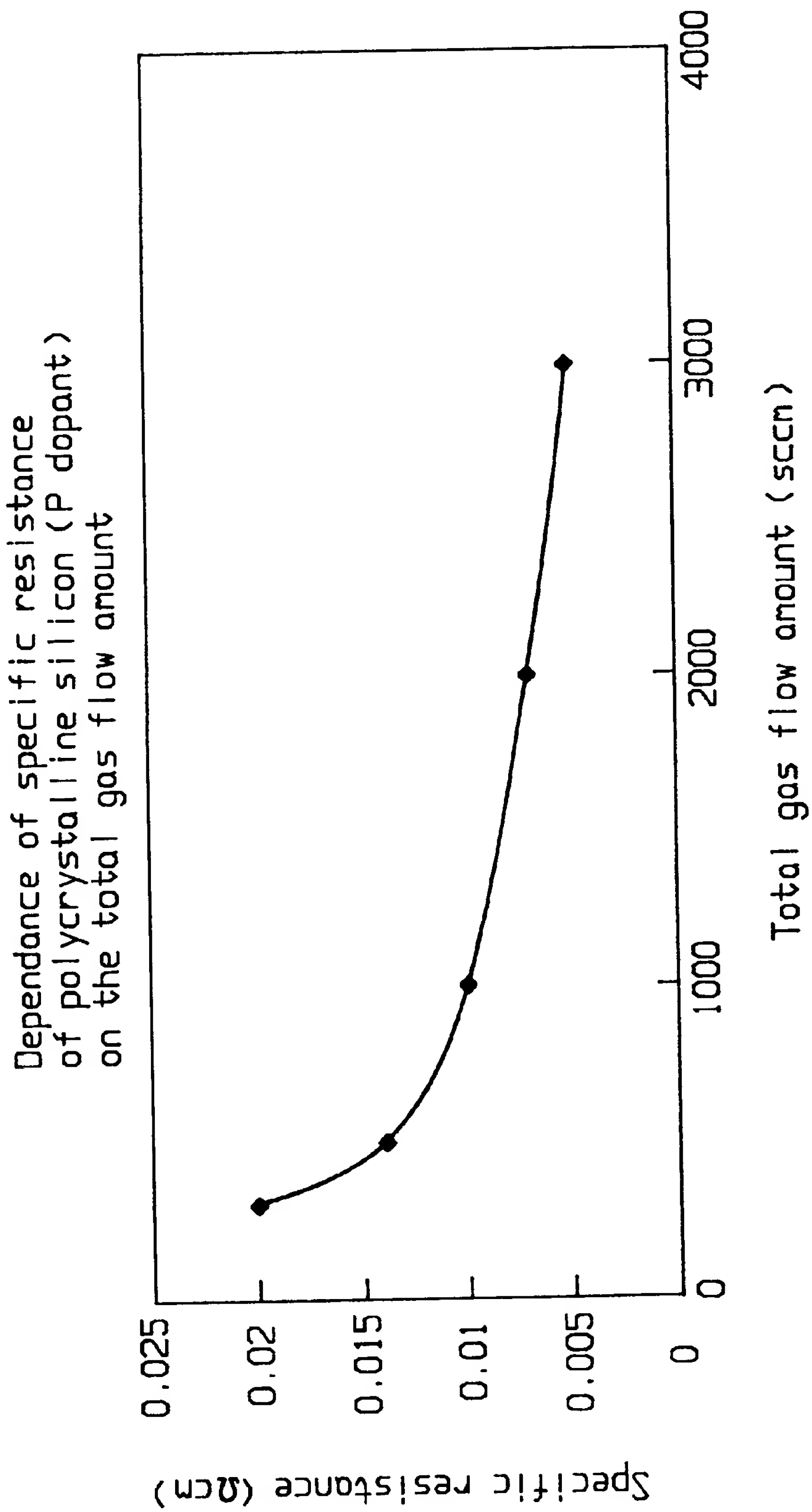

Dependance of specific resistance
of polycrystalline silicon (P dopant)
on the total gas flow amount
Specific resistance (Ωcm)
0.025
0.02
0.015
0.01
0.005
0
0
1000
2000
3000
4000
Total gas flow amount (sccm)

Fig. 76

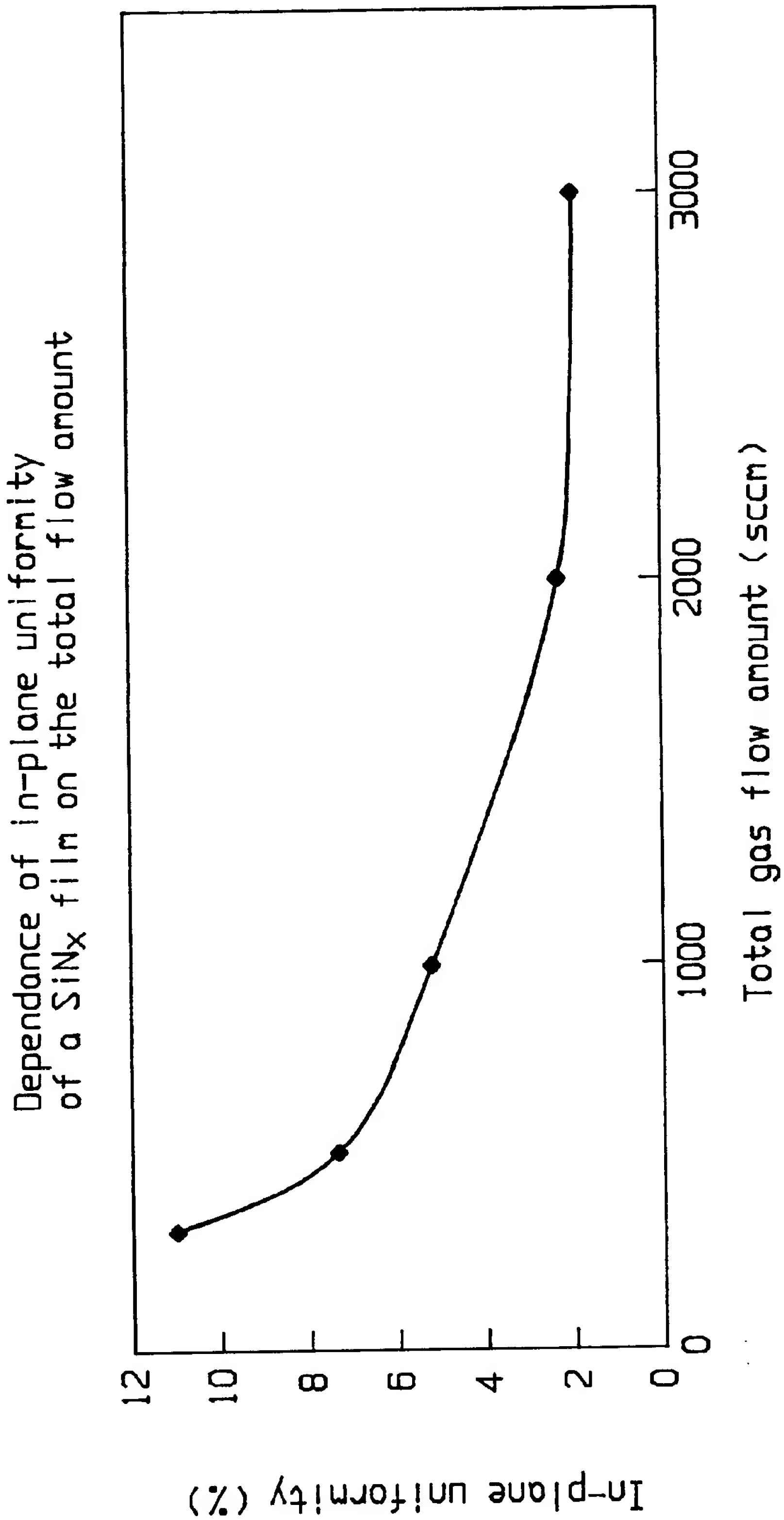

Dependance of in-plane uniformity
of a SiNx film on the total flow amount
In-plane uniformity (%)
0
2
4
6
8
10
12
Total gas flow amount (sccm)
0
1000
2000
3000

Fig. 77

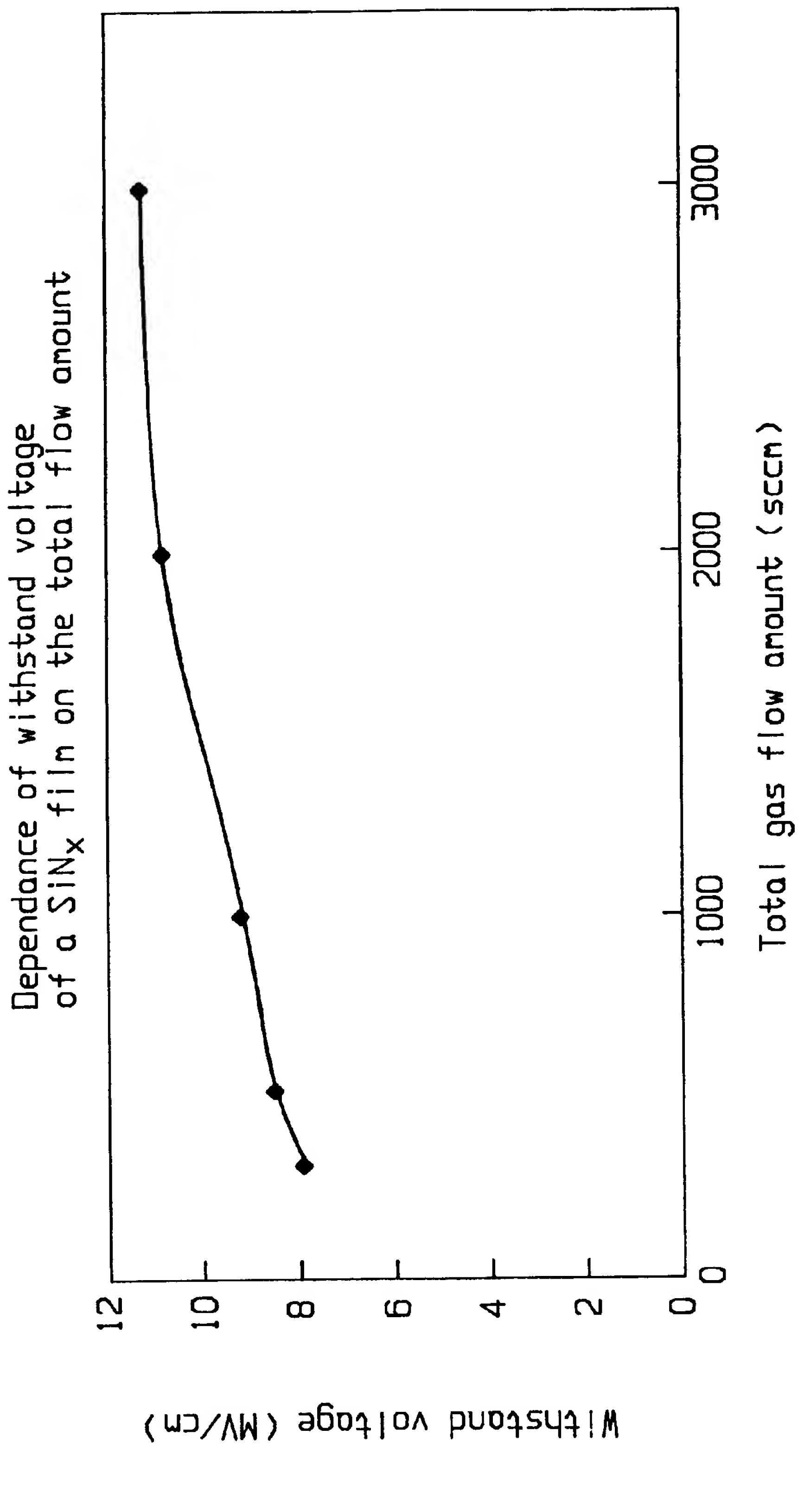

Dependance of withstand voltage
of a SiN_x film on the total flow amount
Withstand voltage (MV/cm)
0
2
4
6
8
10
12
Total gas flow amount (sccm)
0
1000
2000
3000

Fig. 78

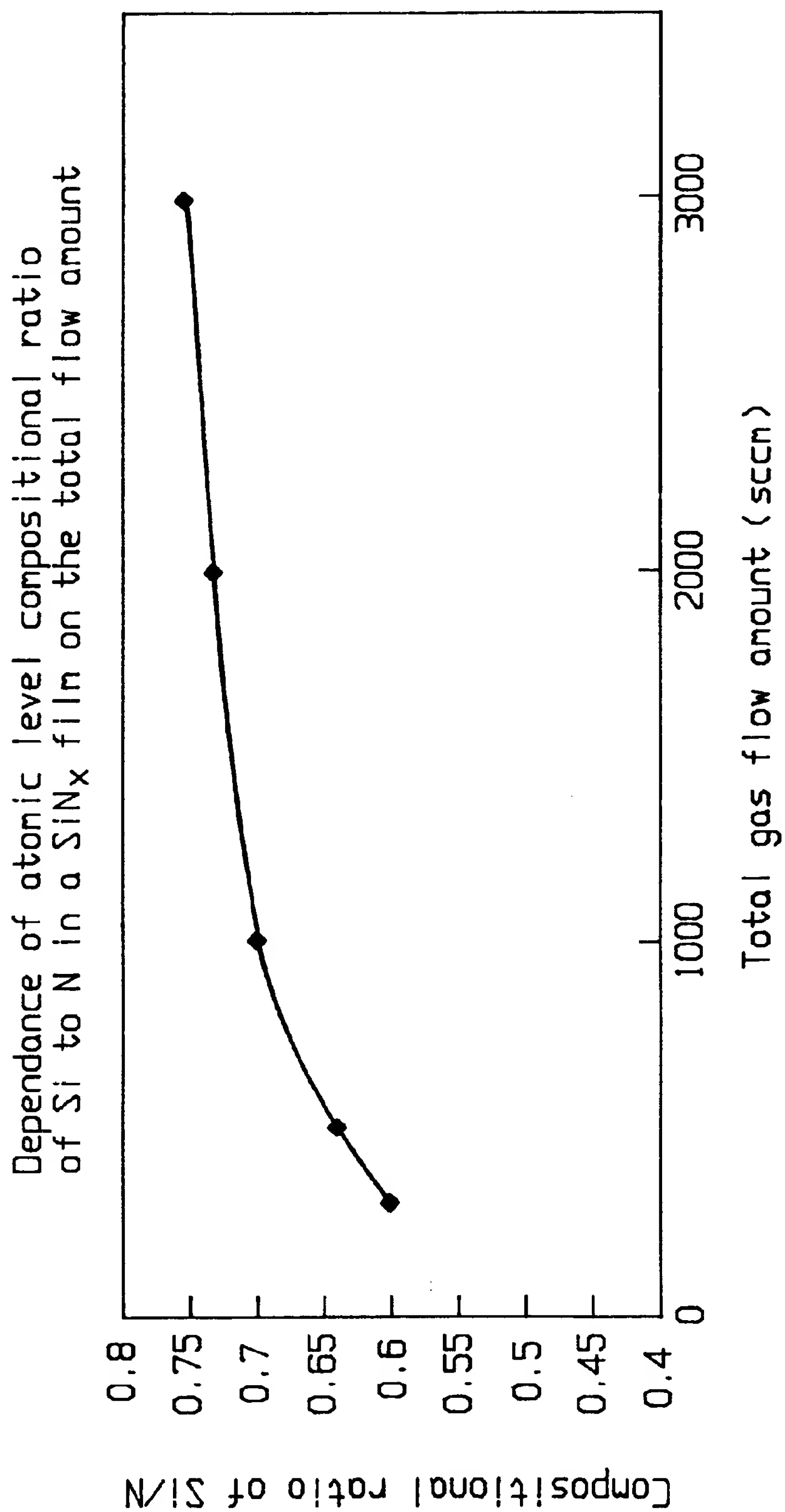

Dependance of atomic level compositional ratio
of Si to N in a SiN_x film on the total flow amount
Compositional ratio of Si/N
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0
1000
2000
3000
Total gas flow amount (sccm)

Fig. 79

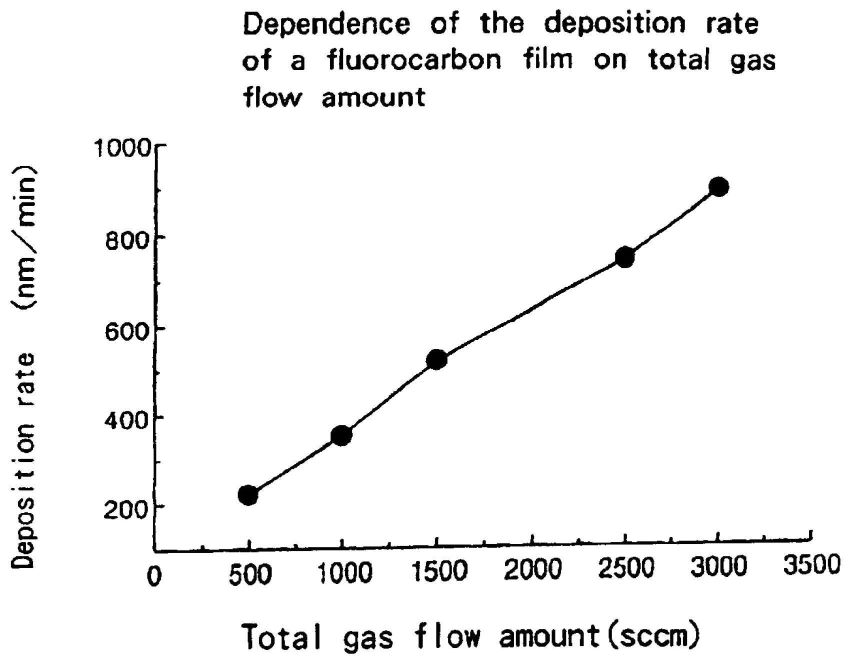

Dependence of the deposition rate
of a fluorocarbon film on total gas
flow amount
Deposition rate (nm/min)
1000
800
600
400
200
0
500
1000
1500
2000
2500
3000
3500
Total gas flow amount(sccm)

Fig. 80

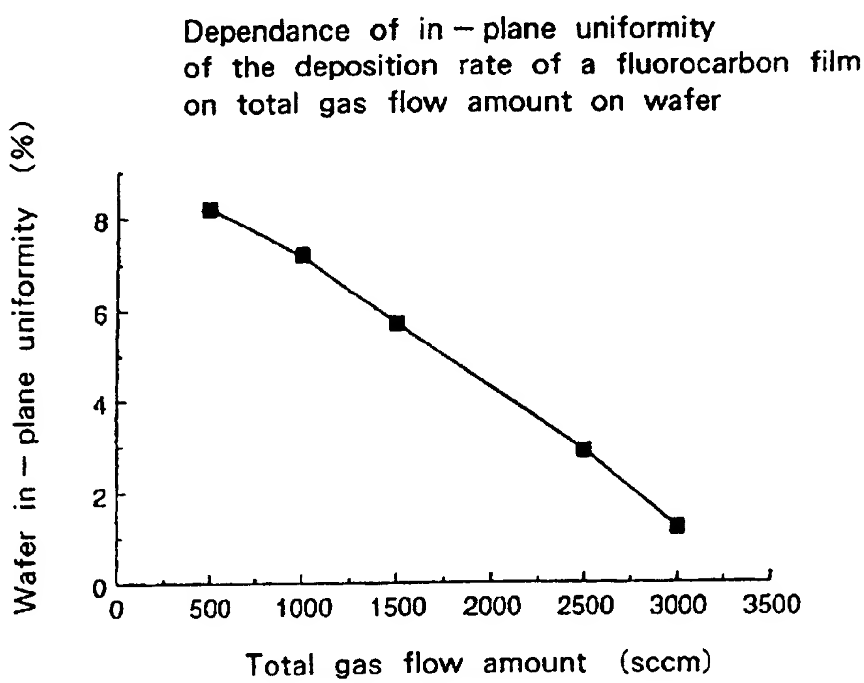

Dependance of in-plane uniformity
of the deposition rate of a fluorocarbon film
on total gas flow amount on wafer
Wafer in-plane uniformity (%)
8
6
4
2
0
0
500
1000
1500
2000
2500
3000
3500
Total gas flow amount (sccm)

Fig. 81

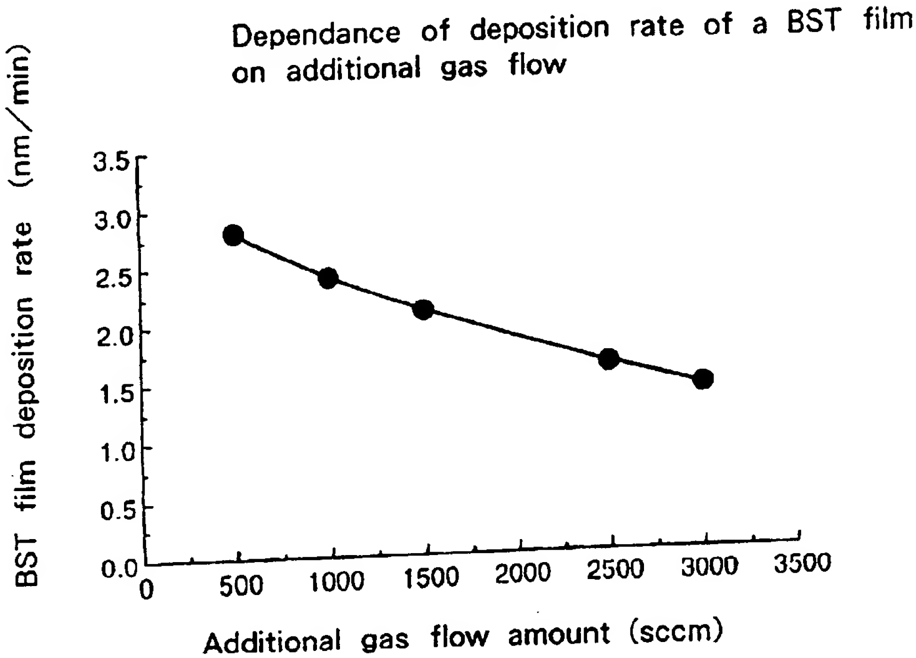

Dependance of deposition rate of a BST film on additional gas flow
BST film deposition rate (nm/min)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
500
1000
1500
2000
2500
3000
3500
Additional gas flow amount (sccm)

Fig. 82

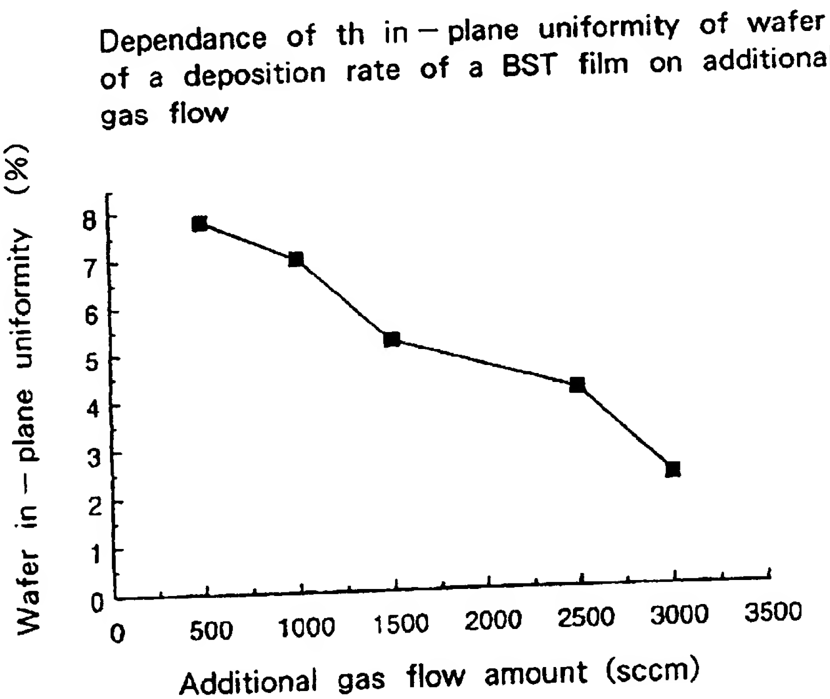
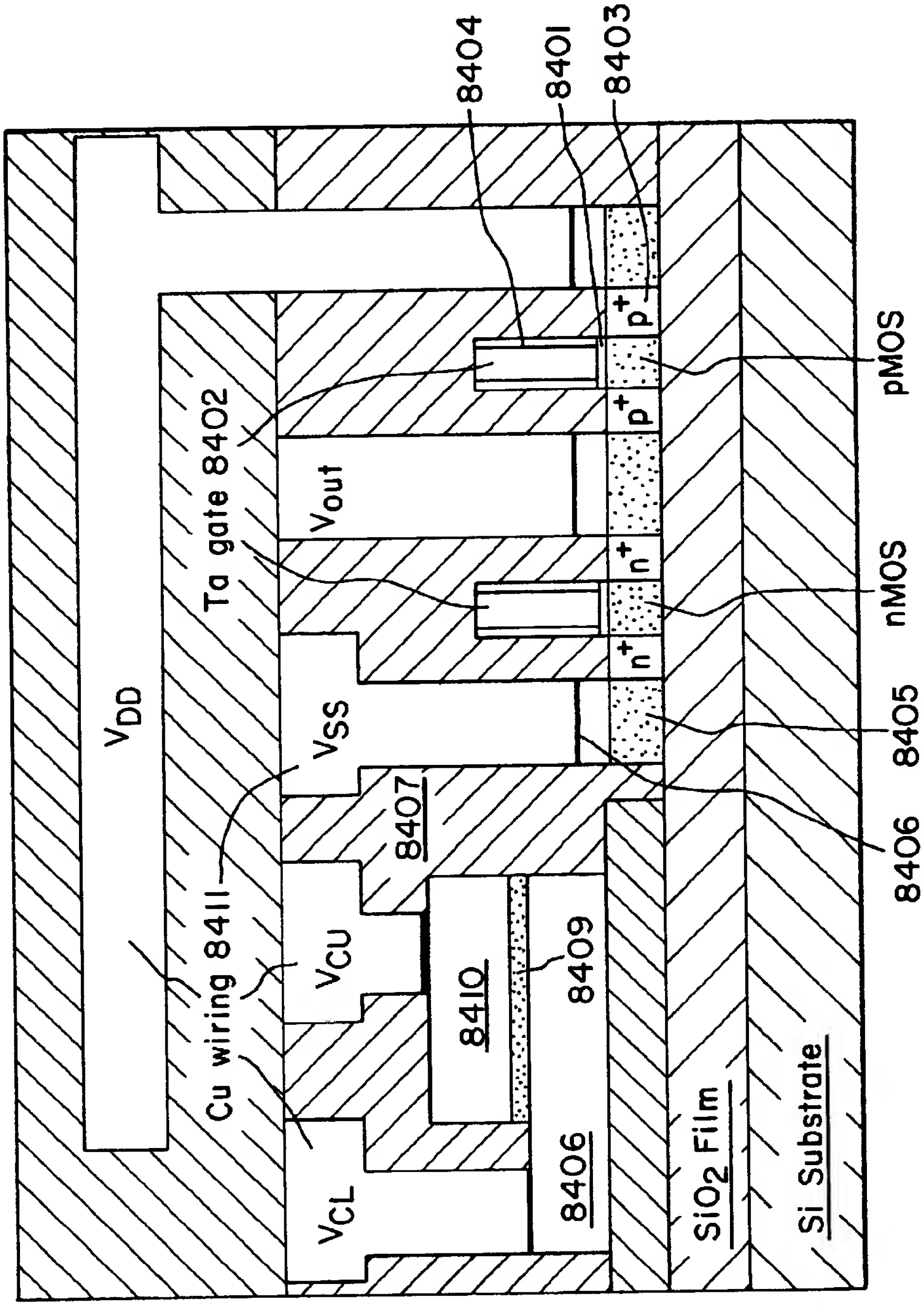

Dependance of th in-plane uniformity of wafer of a deposition rate of a BST film on additional gas flow
Wafer in-plane uniformity (%)
8
7
6
5
4
3
2
1
0
0
500
1000
1500
2000
2500
3000
3500
Additional gas flow amount (sccm)

Fig. 83



8404
8401
8403
p+
p+
pMOS
Ta gate 8402
Vout
n+
n+
nMOS
VDD
VSS
8405
8406
8407
Cu wiring 8411
VCU
8410
8409
VCL
8406
SiO2 Film
Si Substrate

Fig. 84

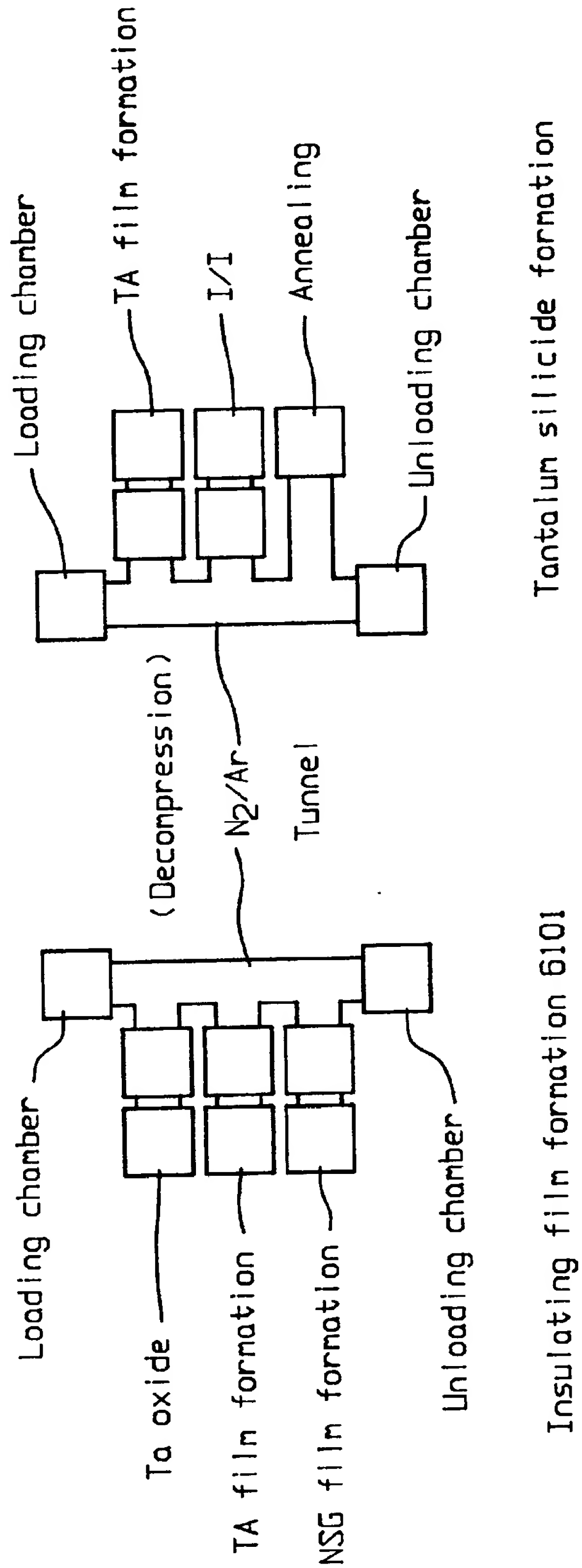


Fig. 85B

Fig. 85A

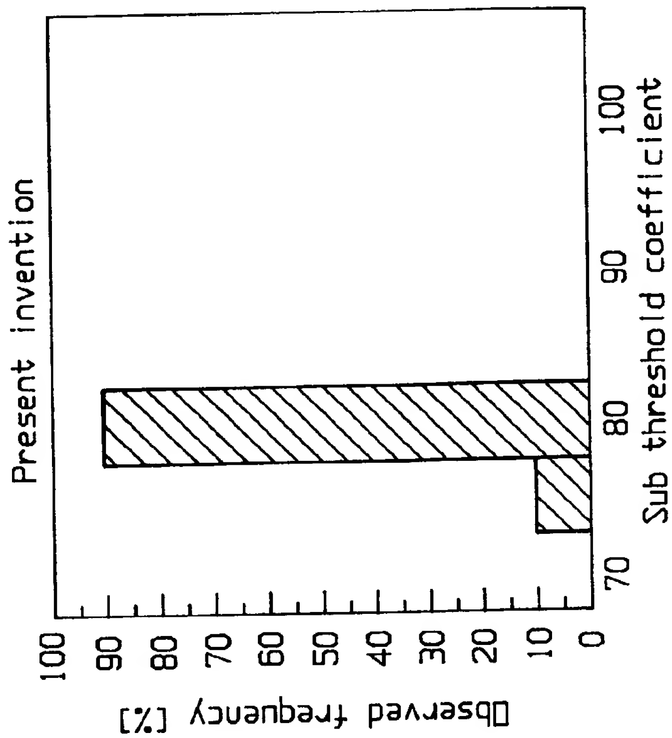


Fig. 86B

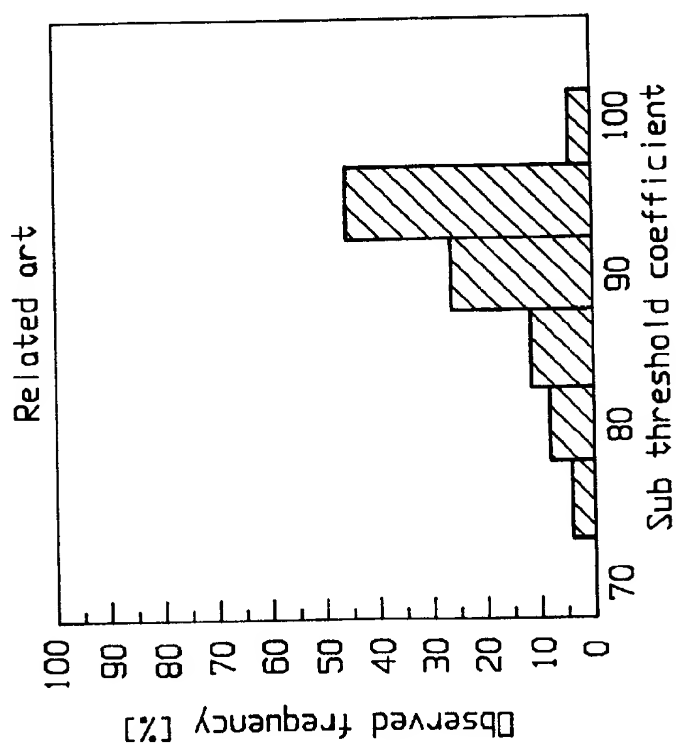


Fig. 86A

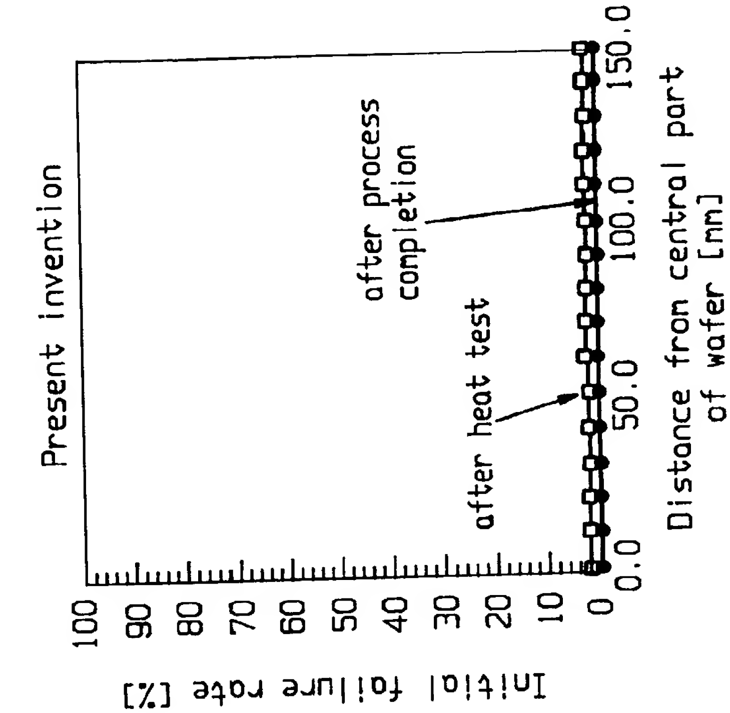


Fig. 87B

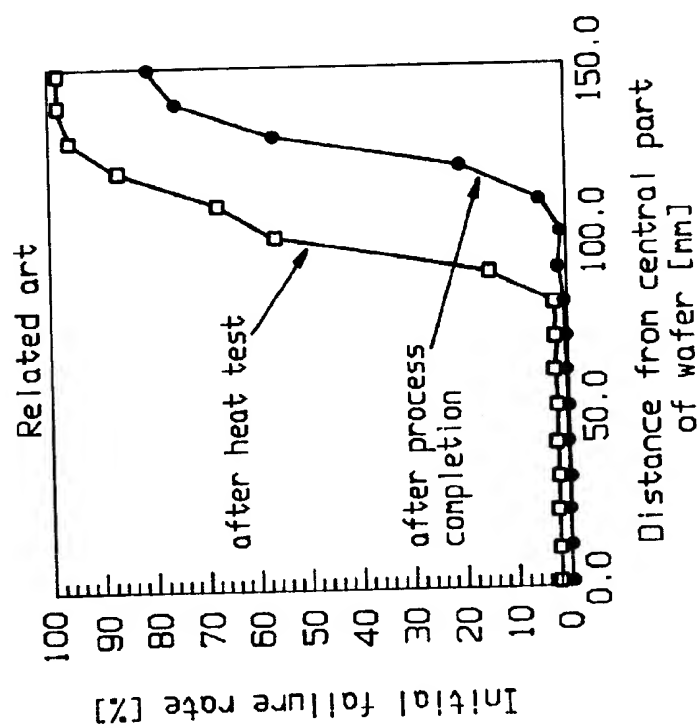


Fig. 87A

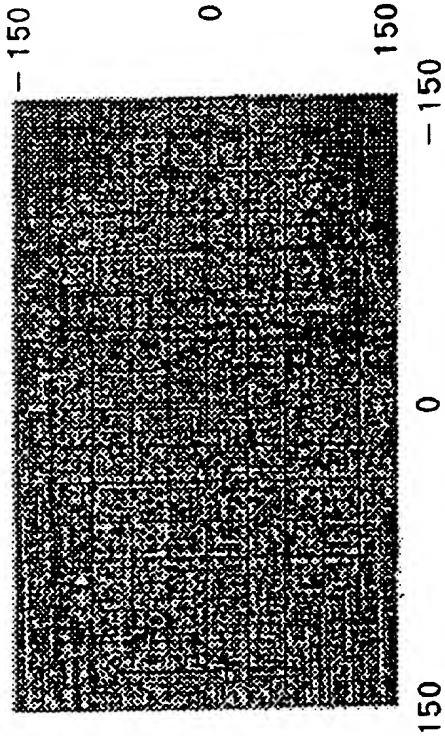
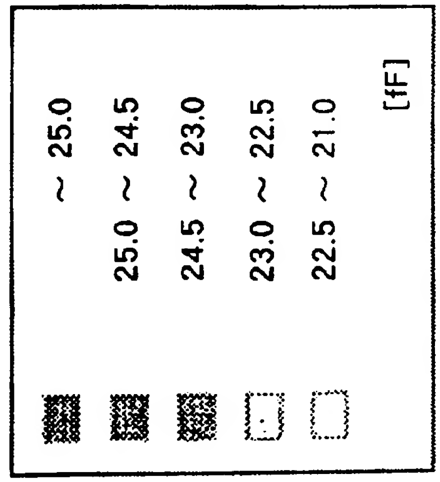


Fig. 88B Present invention



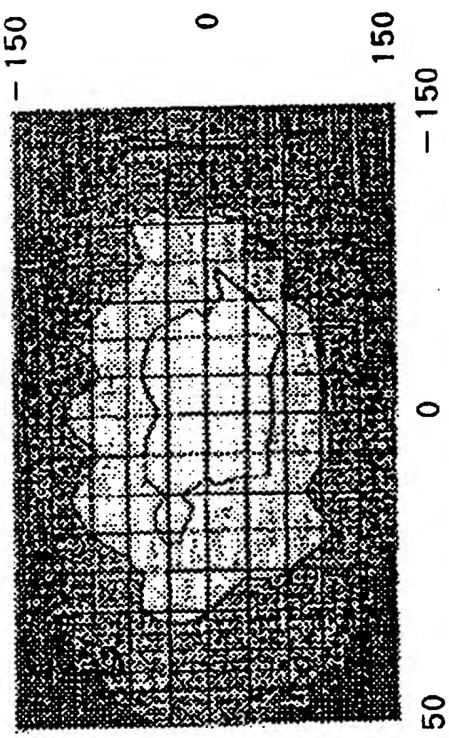


Fig. 88A Related art

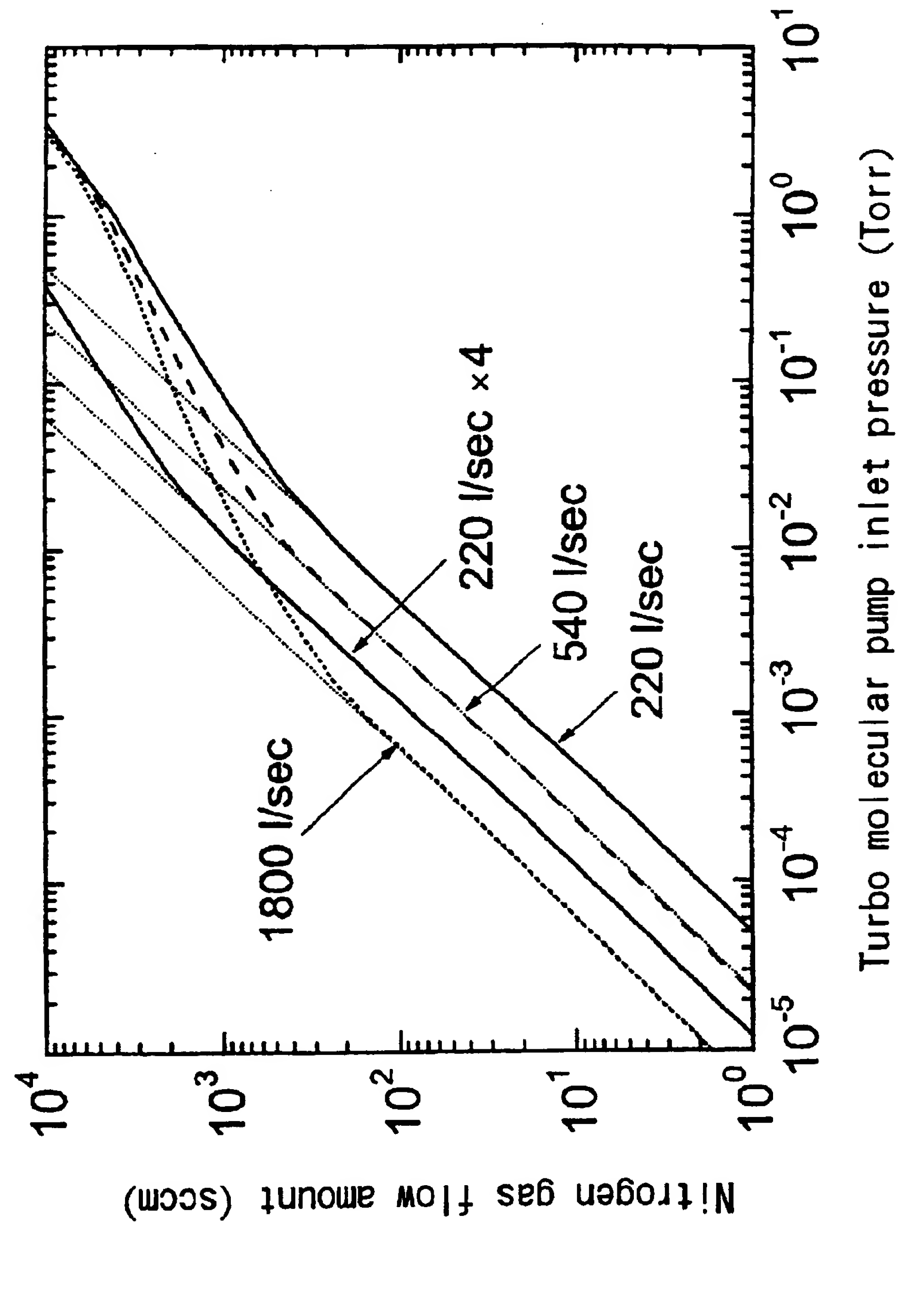
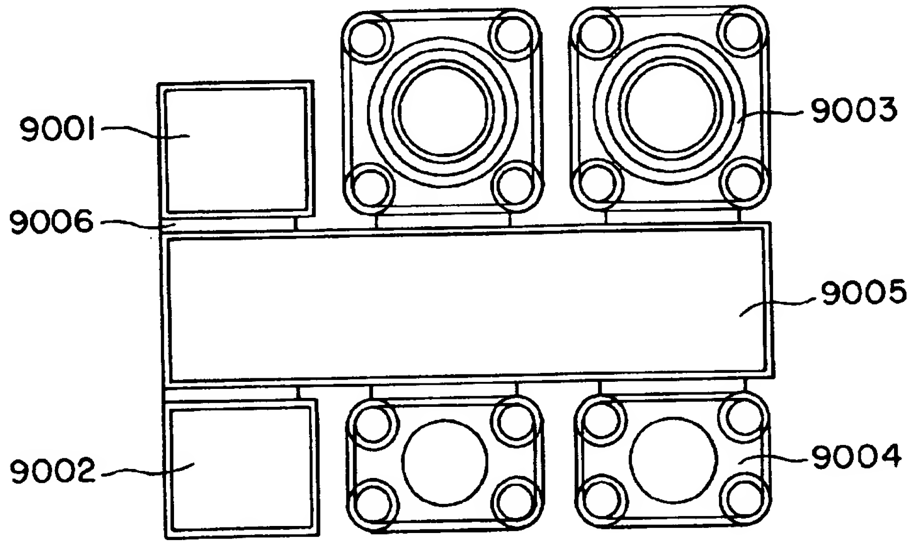
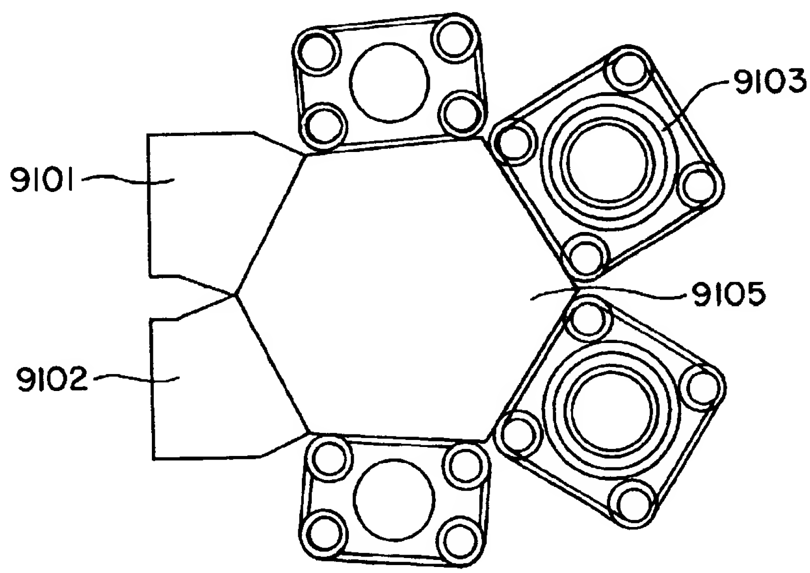

Nitrogen gas flow amount (sccm)
Turbo molecular pump inlet pressure (Torr)
1800 l/sec
220 l/sec ×4
540 l/sec
220 l/sec
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

Fig. 89



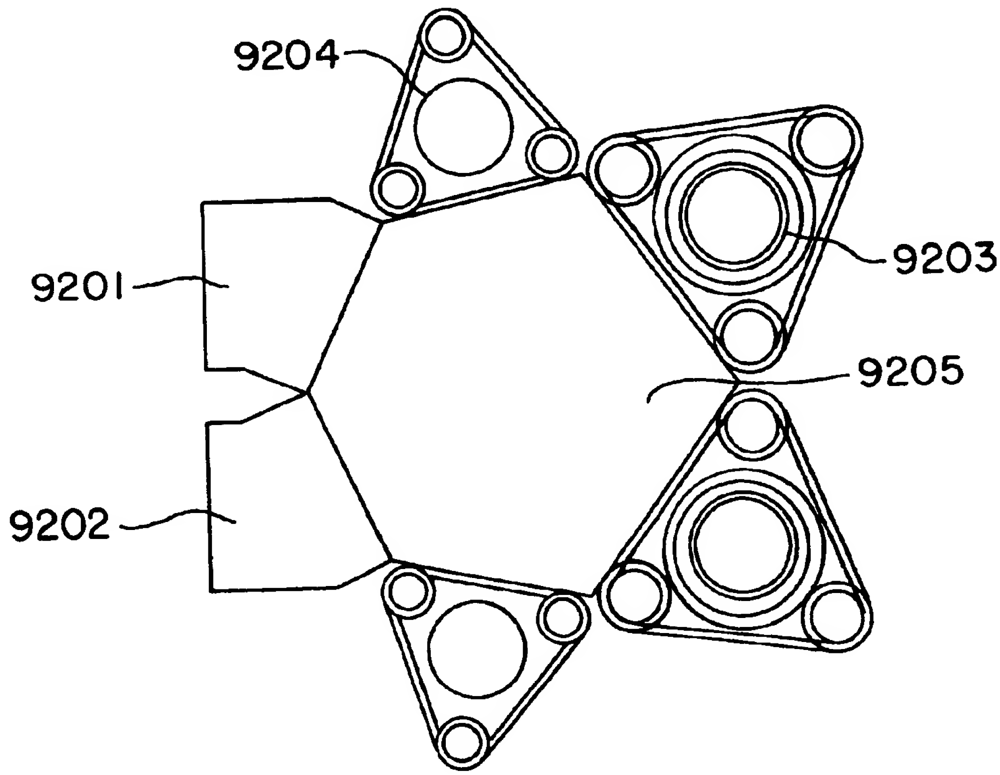
Cluster tool comprising assembly of rectangular process chamber (1)

Fig. 90



Cluster tool comprising assembly of rectangular process chamber (2)

Fig. 91



Cluster tool comprising assembly of triangular process chamber

Fig. 92

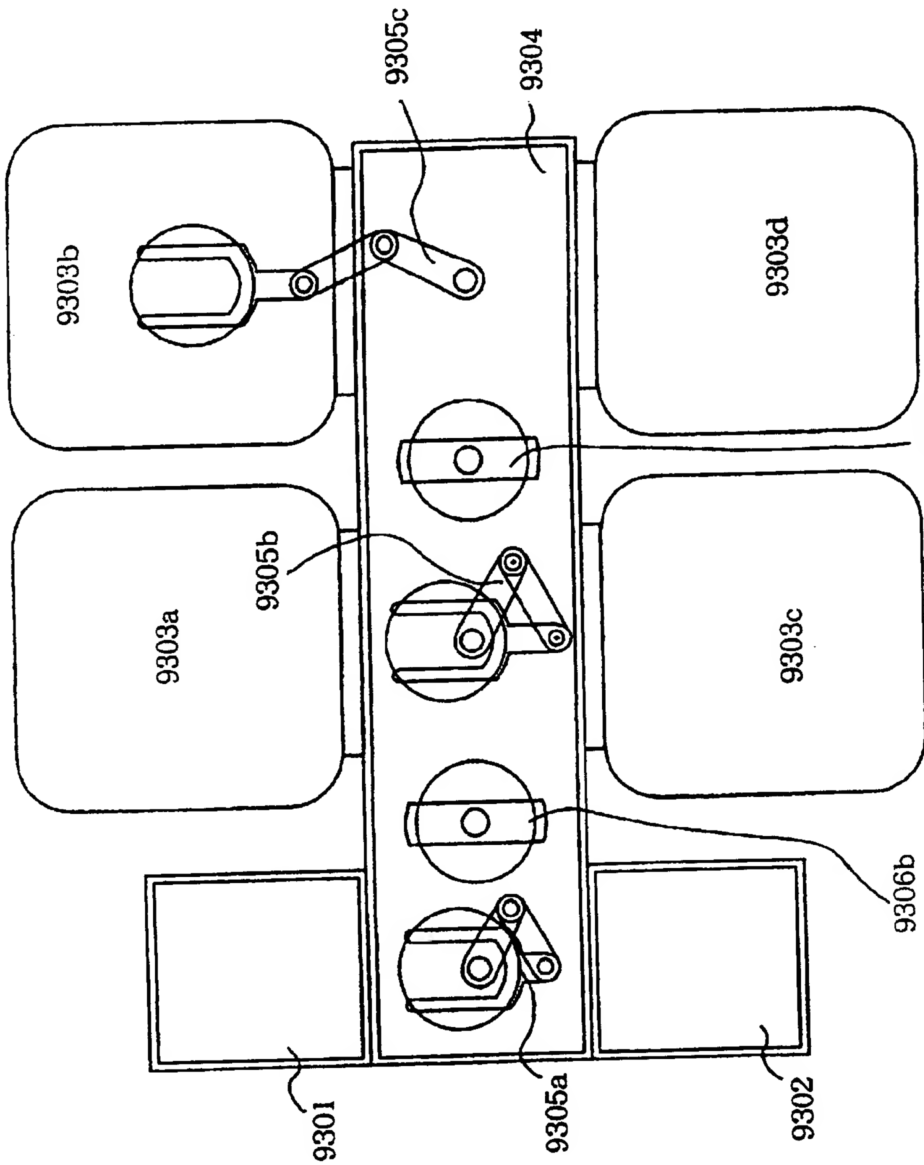

9305c
9304
9303b
9303d
9306a
9305b
9303a
9303c
9306b
9301
9305a
9302

Fig. 93

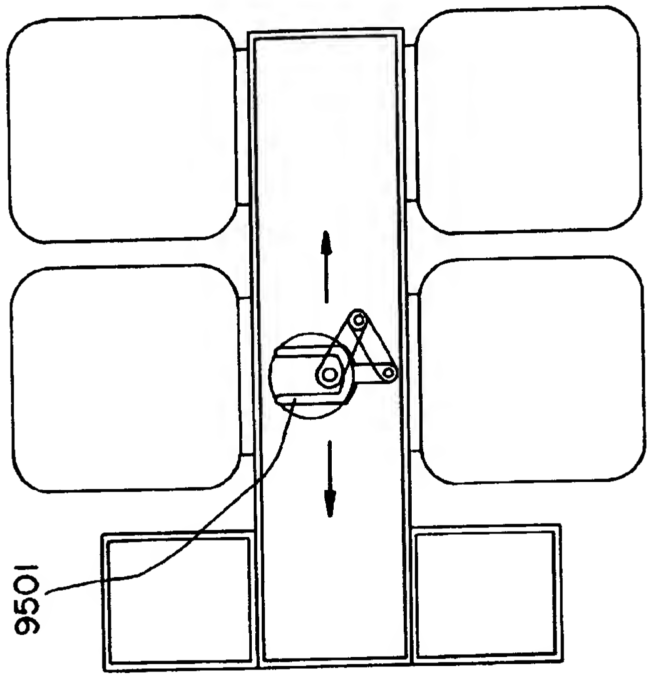


Fig. 95

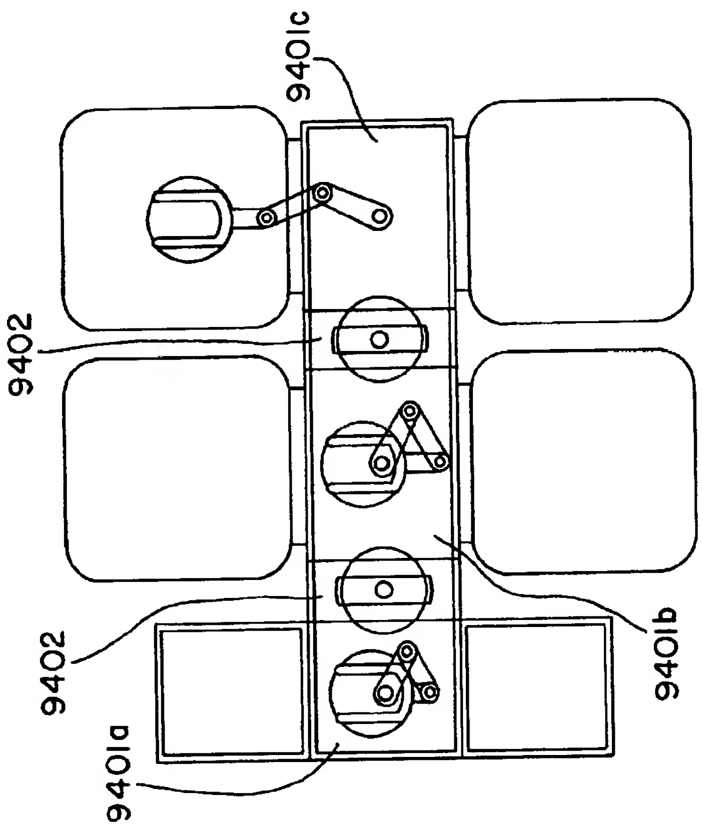


Fig. 94

PLASMA DEVICE

TECHNICAL FIELD

The present invention relates to a plasma device.

BACKGROUND OF THE INVENTION

Recently, accompanying the increase in chip size of ULSI (ultra large scale integrated circuits), there has also been a tendency to increase the diameter of a silicon substrate used as a substrate for the ULSI. Since sheet leaf processing for handling substrates one at a time has become mainstream, if the substrate is increased in diameter there is a need for high speed processing of at least 1 mm per minute in order to maintain high productivity if etching and film forming are carried out. In a plasma device for handling an increased diameter substrate enabling high speed processing, it is essential to be able to generate high density plasma having an electron density in excess of 10^{11} cm^{-3} and to obtain the flow of a large quantity of gas in order to efficiently remove a large amount of reaction products discharged from the substrate surface as a result of the high speed processing. In order to enable the generation of high density plasma, a parallel plate type plasma device introducing a magnetic field has been developed. As a conventional plasma device of this type, a magnetron plasma etching device using a dipole ring magnet is disclosed in, for example, Japanese Patent Laid Open No. Hei. 6-37054.

FIG. **43** is a schematic diagram of the conventional magnetron plasma etching device using a dipole ring magnet. FIG. **43**(*a*) shows the state at the time of etching, and FIG. **43**(*b*) shows the state at the time of conveying the substrate. In the drawings, reference numeral **4301** is a vacuum vessel, reference numeral **4302** is an electrode I, reference numeral **4303** is a substrate in a space **4315**, reference numeral **4304** is a gas introduction opening, reference numeral **4305** is a shower plate, reference numeral **4306** is a dipole ring magnet, reference numeral **43j07** is a bellows, reference numeral **4308** is a porous plate, reference numeral **4309** is a gate valve, reference numeral **4310** is a substrate conveying port, reference numeral **4311** is a gas outlet, reference numeral **4312** is a vacuum pump, reference numeral **4313** is a matching circuit and reference numeral **4314** is a high frequency power source.

At the time of etching, source material gas that has been introduced from the gas introduction opening **4304** is discharged from a plurality of small holes in the shower plate **4305**. This source material gas and reaction product gas discharged from the substrate surface as a result of the etching reaction are discharged to the outside, through a side section of the electrode I **4302**, the porous plate **4308** and the gas outlet **4311**, by the expel pump **4312**. The porous plate **4308** causes a lowering of the gas conductance between a space above the substrate **4303** and the gas outlet **4311**, and is provided so as to make the gas flow substantially uniformly in a direction of rotation of the space above the substrate **4303**. Since the gas is made to flow uniformly in a direction of rotation of the space above the substrate **4303**, the gas conductance between the space above the substrate **4303** and the gas outlet **4311** is inevitably restricted and there is a problem that a large amount of gas can not flow. As a result, in high speed etching on large diameter substrates the etching rate is lowered, and a problem arises that the etching shape degenerates.

At the time of conveying the substrate, the position of the electrode I **4302** is lowered, as in FIG. **43**(*b*), and the substrate is conveyed through the gate valve **4309** and the substrate conveying port **4310** using an external substrate conveyance machine. The bellows **4307** are required in order to cause the electrode I **4302** to move. At the time of plasma generation, power loss occurs due to high frequency current flowing in the bellows **4307**, and there is a problem that the high frequency output power of the high frequency power source **4314** can not be efficiently supplied to the plasma. There is also a problem that a complex structure is required because the electrode I **4302** is made to move.

A device using electron cyclotron resonance (ECR) is also known as a plasma device using microwaves. This device enables excitation of high density uniform plasma on a substrate, but since the method involves high density plasma being excited locally, caused to widely diffuse within the container and uniformly supplied onto a object to be treated, installation of a shower plate is difficult, and it is difficult to promptly remove gases that are reaction by-products.

As a high density plasma device using microwaves, a device using a radial line slot antenna is also known (Japanese patent laid-open No. Hei.8-111297). However, if this device is put to practical use, it is not always possible to cause high density plasma to be generated stably over a long period of time. Also, the conditions for causing the generation of plasma are not definite.

The object of the present invention is to provide a plasma processing device, within a narrow space inside a container that enables uniform formation of a high quality thin film on a large substrate at a low temperature and at high speed, by causing excitation of uniform high density plasma having a low plasma potential over a large surface area, making supply of source material gas uniform, and swiftly removing reaction by-product gases by adopting a structure equivalent to a shower plate. The invention is applicable to plasma processing other than an etching plasma process.

SUMMARY OF THE INVENTION

A plasma device of the present invention comprises:

- a container, the inside of which can be internally decompressed, and part of the inside being formed of a first dielectric plate made of material capable of passing microwaves with almost no loss,
- a gas supply system for supplying essential source material gas so as to cause excitation of plasma inside the container,
- an exhaust system for expelling source material gas supplied into the container and decompressing the inside of the container,
- an antenna, located facing an outer surface of the first dielectric plate and comprised of a slot plate and a waveguide dielectric, for radiating microwaves, and
- an electrode for holding a object to be treated located inside the container, a surface of the object to be treated that is to be plasma processed and a microwave radiating surface of the antenna being arranged in parallel substantially opposite to each other, and the plasma device carrying out plasma processing for the object to be treated, wherein,
  - a wall section of the container outside the first dielectric plate is of a material comprising matter having a specific conductivity of $3.7\times10^{7}\ \Omega^{-1}/m^{-1}$ or more, or the inside of the wall section is covered with this material, and
  - when thickness of the material is d, the specific conductivity of the material is σ, the magnetic permeability of the vacuum is μ_0, and the angular fre-

quency of microwaves radiated from the antenna is ω, the thickness d is larger than $(2/\mu_0\sigma\omega)^{1/2}$.

A plasma processing method of the present invention is a method using a plasma device comprising a container, the inside of which can be internally decompressed, and part of the inside being formed of a first dielectric plate made of material capable of passing microwaves with almost no loss, a gas supply system for supplying essential source material gas so as to cause excitation of plasma inside the container, an exhaust system for expelling source material gas that has been supplied inside the container and decompressing the inside of the container, an antenna, located facing an outer surface of the first dielectric plate and comprised of a slot plate and a waveguide dielectric, for radiating microwaves, and an electrode for holding an object to be treated located inside the container, a surface of the object to be treated that is to be subject to plasma processing and a microwave radiating surface of the antenna being arranged in parallel substantially opposite to each other, and the plasma device carrying out plasma processing for the object to be treated, the power density of microwaves to be input being 1.2 W/cm^2 or more. This method assures stable generation of plasma.

A plasma device of the present invention is provided with an electrode I inside a vacuum container, and a substrate to be subjected to processing using plasma is mounted so as to be connected to this electrode I. Magnetic field applying means I and II are provided outside the vacuum container, for the purpose of applying a magnetic field to the inside of the plasma, and at least some of a gas that has been introduced into the vacuum container is expelled through a space between the magnetic field applying means I and II.

A plasma device of the present invention is provided with two parallel plate type electrodes I and II inside a vacuum container, and a substrate to be subjected to processing using plasma is mounted so as to be connected to either the electrode I or the electrode II. Means for applying a magnetic field to the inside of the plasma are provided, and the electrode II comprises a central section, and an outer section connected to a high frequency power source that can be controlled independently of a high frequency power source connected to the electrode I.

A plasma device of the present invention is provided with an exhaust space formed directly communicating with an inlet of a vacuum pump, to the side of a film forming space above the substrate.

A plasma device of the present invention comprises:

- a container, the inside of which can be internally decompressed, and part of the inside being formed of a first dielectric plate made of material capable of passing microwaves with almost no loss,
- a gas supply system for supplying essential source material gas so as to cause excitation of plasma inside the container,
- an exhaust system for expelling source material gas that has been supplied inside the container and decompressing the inside of the container,
- an antenna, located facing an outer surface of the first dielectric plate and comprised of a slot plate and a waveguide dielectric, for radiating microwaves, and
- an electrode for holding a object to be treated located inside the container, a surface of the object to be treated that is to be subject to plasma processing and a microwave radiating surface of the antenna being arranged in parallel substantially opposite to each other, and the plasma device carrying out plasma processing for the object to be treated, wherein,

an exhaust space formed directly communicating with an inlet of a vacuum pump is provided to the side of a film forming space above the substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a cross section of a device relating to embodiment 1.

FIG. **2** is a plan view showing one example of a radial line slot antenna used in the device of FIG. **1**.

FIG. **3** is the results of a plasma ignition test relating to the first embodiment, showing interdependence between microwave power and chamber material.

FIG. **4** is the results of a plasma ignition test relating to the first embodiment, showing interdependence between plating film thickness and microwave frequency.

FIG. **5** is a cross section of a device relating to embodiment 1 showing the case where a plating layer is provided on an inner surface of the chamber.

FIG. **6** is a cross section of a device relating to embodiment 1 showing the case where the inner surface of the chamber is covered with a plate member comprising a prescribed material.

FIG. **7** is a cross section of a device relating to embodiment 2.

FIG. **8** is an enlarged view of region A in FIG. **7**, and shows a case where a first dielectric plate comes into contact with a first O ring and a metallic thin film **114** is provided on a vacuum sealing region.

FIG. **9** is an enlarged view of region A in FIG. **7**, and shows a case where the first O ring is enveloped by a metallic thin film **5**.

FIG. **10** is a cross section of a device relating to embodiment 3.

FIG. **11** is a graph showing the ion saturation current density in embodiment 3.

FIG. **12** is a cross section of a device relating to embodiment 4.

FIG. **13** is an enlarged view of region B in FIG. **12**.

FIG. **14** is a graph showing the ion saturation current density in embodiment 5.

FIG. **15** is a cross section of a device relating to embodiment 7.

FIG. **16** is a schematic diagram of a tool for confirming the presence or absence of plasma excitation in embodiment 7.

FIG. **17** is a graph showing a relationship between probe voltage and probe current for embodiment 7.

FIG. **18** is a graph showing a relationship between minimum discharge power and Ar pressure for embodiment 7.

FIG. **19** is a partial cross section of a device a device relating to embodiment 8, and shows a case where a cover plate is used.

FIG. **20** is a partial cross section of the device relating to embodiment 8, and shows a case where a slot is reduced in size.

FIG. **21** is a graph showing the ion saturation current density in embodiment 8.

FIG. **22** is a partial cross section of a device relating to embodiment 9.

FIG. **23** is a partial cross section of a device relating to embodiment 10.

FIG. **24** is a cross section of a device relating to embodiment 11.

FIG. 25 is a cross section of a device relating to embodiment 12.

FIG. 26 is a graph showing a relationship between deposition rate of polymer film and chamber internal wall temperature.

FIG. 27 is a cross section of a device relating to embodiment 13.

FIG. 28 is a schematic diagram showing a system when a staged cooler method is adopted in collection and reuse of fluorocarbon type gas in embodiment 14.

FIG. 29 is a graph showing a relationship between average binding energy of fluorine gas and the plasma parameter of the fluorine gas for embodiment 15.

FIG. 30 is a graph showing evaluation results of damage caused by plasma irradiation of AlF_3/MgF_2 alloy, FIG. 30(*a*) showing before NF_3 plasma irradiation and FIG. 30(*b*) showing after 2 hours of NF_3 plasma irradiation.

FIG. 31 is a graph showing distribution of ion saturation current density for embodiment 16.

FIG. 32 is a graph showing distribution of electron temperature for embodiment 16.

FIG. 33 is a graph showing distribution of electron temperature for embodiment 16.

FIG. 34 is a schematic diagram of a system for measuring ion current distribution for embodiment 16.

FIG. 35 is a schematic showing the structure of a single probe used in measurement of electron temperature and electron density for embodiment 16.

FIG. 36 is a graph showing results of plasma etching in embodiment 17.

FIG. 37 is a schematic diagram showing a combination of a cross section of elements of embodiment 18 and a element withstand voltage measurement system.

FIG. 38 is a graph showing results of withstand voltage for embodiment 18.

FIG. 39 is a graph showing results of analyzing chemical binding state of a Si surface, using an X-ray photoelectron spectroscope, for a silicon nitride film in embodiment 28.

FIG. 40 is a schematic diagram showing a combination of a cross section of an element and an element dielectric breakdown injection charge amount measurement system, for embodiment 28.

FIG. 41 is a graph showing results of dielectric breakdown injection charge amount for embodiment 28.

FIG. 42 is a graph showing results of an X ray diffractometer for embodiment 29.

FIG. 43(*a–b*) is a schematic diagram of a conventional magnetron plasma etching device.

FIG. 44 is a schematic diagram showing an example of a plasma device of the present invention.

FIG. 45 is a plan view showing an example of a plasma device of the present invention.

FIG. 46 is a plan view showing an example of a plasma device of the present invention.

FIG. 47 is a plan view showing an example of a plasma device of the present invention.

FIG. 48 is a plan view showing an example of a plasma device of the present invention.

FIG. 49 is a plan view showing an example of a plasma device of the present invention.

FIG. 50 is a plan view showing an example of a plasma treatment device of the present invention.

FIG. 51 is a plan view showing an example of a plasma treatment device of the present invention.

FIG. 52 is a plan view showing an example of a plasma treatment device of the present invention.

FIG. 53 is a plan view showing an example of a plasma device of the present invention.

FIG. 54 is a plan view showing an example of a plasma device of the present invention.

FIG. 55 is a drawing showing an example of means for applying a high frequency to electrode II.

FIG. 56 is a drawing showing an example of means for applying a high frequency to electrode II.

FIG. 57 is a graph comparing displacement in the related art and this embodiment.

FIG. 58 is a drawing showing the manufacturing flow when producing a pattern with this embodiment.

FIG. 59 is a graph comparing specific resistance in the related art and this embodiment.

FIG. 60 is a schematic diagram showing a combination of a cross section of elements of this embodiment and a withstand voltage measuring system.

FIG. 61 is a graph showing results of measuring withstand voltage for this embodiment and the related art.

FIG. 62 is a plan view of a plasma device of the related art.

FIG. 63 is a graph showing distribution of film thickness inside the surface of a wafer of silicon oxide film.

FIG. 64 is a schematic diagram showing a combination of a cross section of elements of this embodiment and a system for measuring dielectric breakdown injection charge amount.

FIG. 65 is a graph showing results of measuring dielectric breakdown injection charge amount.

FIG. 66 is a graph showing distribution of film thickness inside the surface of a wafer of direct nitride film.

FIG. 67 is a graph showing results of a system for measuring barrier properties of a direct nitride film.

FIG. 68 is a graph showing a relationship between amounts of oxygen and carbon, and total flow amount of process gas.

FIG. 69 is a drawing showing an example of a mask structure for X ray lithography.

FIG. 70 is a schematic diagram showing a diamond thin film permeability measurement system.

FIG. 71 is a graph showing the results of evaluating a diamond thin film.

FIG. 72 is a graph showing dependence of surface roughness of a polycrystalline silicon thin film on total flow amount.

FIG. 73 is a graph showing dependence of uniformity of a glass substrate surface of a polycrystalline silicon thin film on total gas flow amount.

FIG. 74 is a graph showing dependence of crystallite size of polycrystalline silicon on total gas flow amount.

FIG. 75 is a graph showing dependence of the amount of hydrogen in a polycrystalline silicon film on total gas flow amount.

FIG. 76 is a graph showing dependence of the specific resistance of polycrystalline silicon (P dopant) on total gas flow amount.

FIG. 77 is a graph showing dependence of the in-plane uniformity of a SiNx film on total gas flow amount.

FIG. 78 is a graph showing dependence of the withstand voltage of a SiNx film on total gas flow amount.

FIG. 79 is a graph showing dependence of the atomic level compositional ratio of Si to N in a SiNx film on total gas flow amount.

FIG. 80 is a graph showing dependence of the deposition rate of a fluorocarbon film on total gas flow amount.

FIG. 81 is a graph showing dependence of the deposition rate of a fluorocarbon film on total gas flow amount.

FIG. 82 is a graph showing the dependence of additional gas flow on the deposition rate of a BST film.

FIG. 83 is a graph showing the dependence of the in-plane uniformity of wafer of a deposition rate of a BST film on additional gas flow.

FIG. 84 is a cross section of a device manufactured using the present invention.

FIG. 85 is a drawing showing process cluster tools for formation of an insulating film and formation of tantalum silicide.

FIG. 86 is a drawing showing distribution of a subthreshold coefficient of a tantalum oxide gate insulation film MOSFET.

FIG. 87 is a graph showing initial damage rates of samples of the present example and the related art.

FIG. 88 is a drawing showing in-plane uniformity of a tantalum oxide capacitor.

FIG. 89 is a graph showing displacement of a turbo molecular pump.

FIG. 90 is a plan view showing a practical example of a plasma device of the present invention.

FIG. 91 is a plan view showing a practical example of a plasma device of the present invention.

FIG. 92 is a plan view showing a practical example of a plasma device of the present invention.

FIG. 93 is a drawing showing the layout of a wafer conveyance port inside a wafer conveyance chamber of FIG. 90.

FIG. 94 is a drawing showing the layout of a wafer conveyance port inside a wafer conveyance chamber of FIG. 90.

FIG. 95 is a drawing showing the layout of a wafer conveyance port inside a wafer conveyance chamber of FIG. 90.

DESCRIPTION OF THE NUMERALS

100 container
101 chamber
102 first dielectric plate
103 waveguide dielectric plate
104 object to be treated
105 plasma
106 antenna slot plate
107 coaxial tube
108 antenna guide
109 electrode
110, 110', 110", 111 slot
112 plating layer
113 plate member
114, 115 metallic thin film
116 second dielectric plate
117 gas inlet
118 means **8** for preventing warping of slot plate
119 cover plate
120 means **6** for maintaining antenna at fixed temperature
121 means **7** for maintaining first dielectric plate at fixed temperature
122 means **9** for detecting presence or absence of plasma generated in space **2**
123 window formed of material transparent to light
124 light inlet
125 Xe lamp
201 radial line slot antenna
202 first O ring
205 space **3**
206 space **4**
207 space **5**
208 space **1**
209 space **2**
214 metallic thin film
216 second O ring
301 upper glass plate
302 lower glass plate
303 middle glass plate
304 space **6**
305 tungsten wire
306 aluminum wire covered with ceramic
401 disk-shaped electrode
402 pin
403 aluminum wire
404 resistor
405 operational amplifier
406 A-D converter
407 computer
408 stepping motor
409 power supply
501 chamber
502 plasma
503 object to be treated
504 electrode
505 heater
506 laser
507 photodetector
601 probe tip
602 silver wire
603 ceramic tube
604 SUS tube
605 ring seal
606 lobe measurement system
701 object to be treated
702 field oxidation film
703 gate oxidation film
704 gate electrode
705 probe
706 voltmeter
707 voltage applying means
801 object to be treated
802 field oxidation film
803 gate nitride film

804 gate electrode
805 probe
806 voltmeter
807 constant current source
808 ammeter
4301 vacuum container
4302 electrode I
4303 base
4304 gas inlet
4305 shower plate
4306 dipole ring magnetron
4307 bellows
4308 porous plate
4309 gate valve
4310 base conveyance port
4311 gas outlet
4312 vacuum pump
4313 matching circuit
4314 high frequency power supply
4406 vacuum container
4407 electrode I
4408 base
4409 focus ring
4410 shower plate
4411 electrode II
4412 gas inlet
4413 magnetic field applying means
4414 vacuum pump
4415 matching circuit I
4416 high frequency power supply I
4417 matching circuit II
4418 high frequency power supply II
4501 vacuum container
4502 gas inlet
4503 magnetic field applying means
4504 gas outlet
4505 gate valve
4601 vacuum container
4602 gas inlet
4603 magnetic field applying means
4604 gas outlet
4605 gate valve
4701 vacuum container
4702 gas inlet
4703 magnetic field applying means
4704 gas outlet
4705 vacuum pump
4706 gate valve
4801 vacuum container
4802 vacuum pump
4901 vacuum container
4802 vacuum pump
5001 vacuum container
5002, 5003 means for applying magnetic field inside the container
5004 electrode I
5005 electrode II

5006, 5007 means for expelling source material gas and reaction product gas
5004 electrode I
5005 electrode II
5006, 5007 means for expelling source material gas and reaction product gas
5108 means for applying a high frequency
5204 electrode I
5206, 5207 means for expelling source material gas and reaction product gas
5301 vacuum container
5302 source material gas inlet
5303 vacuum pump
5304 dielectric plate I
5305 antenna
5306 electrode I
5307 shower plate
5308 base
5309 reflector
5301 vacuum container
5302 electrode I
5303 electrode II
5404 target
5405 base
5406 matching circuit I
5408 high frequency power source I
5412 matching circuit II
5413 high frequency power supply II
5414 means for applying magnetic field
5410 auxiliary electrode A
5411 auxiliary electrode B
5414*a* magnetic field applying means
5415 vacuum pump
5501 electrode IIa
5502 electrode IIb
5503 target
5504 high frequency power supply I
5505 matching circuit I
5506 high frequency power supply II
5507 matching circuit
5508 phase control circuit
5601 electrode Ia
5602 electrode Ib
5603 target
5605 matching circuit

DETAILED DESCRIPTION OF THE INVENTION

Best Mode of Practicing the Invention

(1) In the plasma device of the present invention, an antenna for irradiating microwaves is provided on the outer side of a container, with a first dielectric plate interposed between the antenna and the container. Because the first dielectric plate is made of a material that can transmit microwaves with almost no loss, it becomes possible to excite plasma inside the container by irradiating microwaves from outside the container, so that the antenna is not directly exposed to the source material gas and the reaction

by-product gas. Also, an electrode for holding an object to be treated is provided inside the container, and a microwave emitting surface of the antenna and a surface of the object to be treated that is to be subjected to plasma processing are arranged opposite to each other and substantially in parallel, which means that it is easy to reduce a space between these two surfaces, and it is possible to increase the flow rate of source material gas and reaction by-product gas, and to swiftly remove the reaction by-product gas. Further, a wall section of the container other than the first dielectric plate is either a member comprising a material having specific conductivity higher than that of aluminum, or the outside of this wall section is covered with the member, and if thickness of the material is d, the specific conductivity of the material is σ, the magnetic permeability of the vacuum is μ_0, and the angular frequency of microwaves radiated from the antenna is ω, the thickness d is larger than a skin depth (invasion length) determined from $(2/\mu_0\sigma\omega)^{1/2}$. This means that microwaves introduced into the container are subjected to almost no loss, and can be caused to propagate. As a result, plasma can be excited at a low output, and stable plasma excitation becomes possible.

A first O ring having a function of a vacuum seal is located between the inner surface of the first dielectric plate and the wall section of the container, and by providing a member formed of a conductive means as means I for preventing the first O ring from being directly exposed to the microwaves radiated from the antenna at least at a surface of the first dielectric plate coming into contact with the O ring, leakage is prevented, and it is possible to increase the service life of the O ring and reduce microwave loss. In plasma devices using microwaves, leakage occurred easily. The inventor of this application has been painstakingly searching for the reason why leakage occurs easily when microwaves are used, and has discovered that the cause lies with the O ring.

Specifically, the O ring absorbs microwave energy, with the result that the O ring becomes overheated. Also, the surface becomes molten. If the O ring overheats and the surface melts, leakage will occur. The above describes the reason why leakage occurs easily when microwaves are used, and the inventor of this application was the first to discover this. In the case where microwaves were used, it was not foreseen that the O ring would be exposed to such high temperatures. It is possible to prevent overheating of the O ring and melting of the surface due to the provision of a thin film, formed of a conductive material (for example a metallic material), on at least a surface of the first O ring that comes into contact with the first dielectric layer. This thin film formed of a conductive material can be provided by applying a film on the first dielectric plate, and can be provided by coating the dielectric film using painting, vapor deposition or another method. As the conductive material, it is possible to use titanium, for example.

Also, a thin film made of a conductive material is preferably provided on the surface of the O ring. Titanium coating can also be carried out in this case. Material having low dielectric loss is preferably used in the O ring itself constituting a foundation. For example, BAITON (Trade name) can be used.

This thin film is preferably formed of a material having a specific conductivity of at least $3.7\times10^7\ \Omega^{-1}\bullet m^{-1}$, and preferably has a thickness of at least 10 μm. By providing a thin film having such specific conductivity and thickness, leakage is reduced still further, the service life of the O ring is increased and it is possible to provide a plasma device with low microwave loss.

A first O ring having a function of a vacuum seal is located between the inner surface of the first dielectric plate and the wall section of the container, and by providing means **2** for preventing the first O ring from being directly exposed to the microwaves radiated from the antenna on the surface of the first O ring, it is possible to achieve a proposed leakage amount, prolonged service life of the first O ring, and reduced microwave loss.

By providing a second dielectric plate having a gas inlet for substantially uniform supply of a desired gas between the first dielectric plate and an electrode for holding the object to be treated, it is possible to uniformly supply the source material gas into the container, and to uniformly remove the reaction by-product gas.

This second dielectric plate isolates the vacuum from the atmosphere. Accordingly, the antenna does not reside in the vacuum. If the antenna enters the vacuum, the antenna will be corroded, and cooling is difficult.

A second O ring having a function of a vacuum seal is located between the inner surface of the second dielectric plate and the wall section of the container, and by providing means **3** for preventing the second O ring from being directly exposed to the microwaves radiated from the antenna on an inner surface or an outer surface of the second dielectric plate, it is possible to prevent leakage, prolong the service life of the second O ring, and reduce microwave loss.

A second O ring having a function of a vacuum seal is located between the inner surface of the second dielectric plate and the wall section of the container, and by providing means **4** for preventing the second O ring from being directly exposed to the microwaves radiated from the antenna on the surface of the second O ring, it is possible to prevent leakage, prolong the service life of the second O ring, and reduce microwave loss.

By selecting a material having a dielectric loss angle tan δ less than 10^{-3} as the material of the first dielectric plate or the second dielectric plate, it becomes possible to cause microwaves radiated from the antenna positioned outside the container to be transmitted with virtually no loss, and it is possible to achieve a reduction in microwave loss.

The frequency of the microwaves fed to the antenna is at least 5.0 GHz, and if the distance of a space **1** between the first dielectric plate and the second dielectric plate is less than 7 mm, plasma excitation is not caused in the space **1**, and there is no generation of reaction by-products caused by discharge. Accordingly, it becomes possible to avoid a phenomenon where reaction by-products disturb the supply of source material gas. It is also possible to prevent any detrimental affect on processes such as formation of the thin film on the object to be treated, nitriding or oxidation of the object to be treated, or etching of the object to be treated, etc. by the reaction by-products.

By providing means **5** for generating a differential pressure so that a pressure **1** of space **1** between the first dielectric plate and the second dielectric plate is higher than a pressure **2** of space **2** where an electrode for holding the object to be treated is located, and is surrounded by the second dielectric plate and a wall section of the container other than the second dielectric plate, there is no generation of reaction by-products due to discharge. The differential pressure can be easily provided by varying the pressure of the source material gas and the degree of vacuum inside the container.

By making the slots, positioned in a section where the density of plasma generated in the space **2** is locally high, smaller in diameter than the remaining slots, screening the slot, or not providing the slot at all, the output power of the microwaves is partially reduced in the slot plate functioning

as a radiating surface of the microwaves and it is possible to make the plasma density more uniform. The position where the plasma density becomes locally high is changed depending on device conditions etc., which means, for example, that it is best to initially carry out trials with the same slot diameter, and to find out the part where plasma density becomes locally high using this test.

In the present invention, a space is formed between an antenna and a first dielectric plate. In a plasma device of the related art using microwaves (for example Japanese Patent laid-open No. Hei. 8-111297) the antenna and the first dielectric plate are stuck together. The antenna usually has a thickness in the region of 0.3 mm, and is formed of a copper plate. However, experimentation carried out by the present inventor indicates that in the case of using microwaves the antenna reaches a high temperature in the region of 150° C., and the thickness of the antenna is locally reduced accompanying expansion in due to the heat. As a result, the radiating characteristics of microwaves from the antenna change and the plasma become non-uniform.

In the present invention the antenna and the first dielectric plate are not stuck together and a space is formed between the two, which means that a spacer formed of an elastic body touching the antenna can be interposed in this space, and localized deflection of the antenna does not occur, even if there is expansion due to heat, and it is possible to obtain a stable plasma It is possible to use, for example, silicon rubber, TEFLON (trade name) etc. as the spacer formed of an elastic member.

Also, if means for supplying a heating medium is connected to this space, a heating medium can be supplied into the space, and it is possible to cool the antenna. By cooling the antenna it becomes possible to prevent deflection of the antenna due to heat without using the spacer. Obviously, it is also possible to cool the antenna using the spacer.

Supply of the heating medium into the space formed by the antenna and the first dielectric plate is one function of the means **6** for cooling the antenna, but besides the means **6** it is possible to form a passage in an antenna guide, and to connect a line for supplying a heating medium to this passage.

By providing means **7** for cooling the first dielectric plate close to the first dielectric plate, source material gas to be supplied can be supplied onto the surface of the object to be treated while being maintained at a fixed temperature. Also, using the means **7** bending of the slot plate is prevented, microwaves can be radiated to the inside of the container with almost no loss and it is possible to cause excitation of stable plasma.

By providing means **8** for preventing bending of the slot plate, a highly efficient parallel beam of microwaves can be radiated to the inside of the container which means that it is possible to cause excitation of stable plasma.

By providing means **9** for detecting the presence or absence of plasma generated in the space **2**, it is possible to prevent the inside of the container and the object to be treated etc, being carelessly heated by microwaves radiated from the antenna, and to thus prevent damage.

Since a structure is provided inside the container for respectively raising the temperature of the container wall surface and the outer part of the object to be treated to at least 150° C., emitted gas that hinders the process is reduced, and it is possible to prevent reattachment of reaction by-products.

If a structure (for example a heater) for raising the temperature within units constituting an exhaust system is provided in the exhaust system, the temperature within the exhaust system is raised by this structure and it is possible to prevent reaction byproducts being attached to internal walls of the units.

If a structure is provided for heating the object to be treated, it is possible to compensate for insufficient energy during plasma ion exposure by raising the temperature of the object to be treated.

If a structure for carrying out recovery and recycling of fluorocarbon type gas is provided downstream of the exhaust system, it is possible to carry out recycling by adopting a staged cooling system to gradually cool from a high boiling point gas through liquefaction, distillation and purification to a liquid.

The inside of the container can be cleaned by causing generation of a plasma inside the container having high ion radical density and low plasma potential. The inside of the container at this time can preferably be made of an alloy exhibiting extremely good plasma resistance (AlF_3/MgF_2).

By providing an electrode having the function of holding the object to be treated with means for applying a d.c. bias and/or and a.c. bias, it is possible to increase the ion energy radiated to the object to be treated. For example, when adopted plasma etching, it is possible to realize high speed etching with good uniformity.

Using the plasma device of the present invention, it is possible to uniformly carry out etching processing, direct oxidation processing and direct nitriding processing on the surface of an object to be treated having a large surface area, and uniform film formation at low temperature and high speed is possible.

(2) FIG. **44** is a schematic drawing showing an example of a plasma device of the present invention. FIG. **44**(*a*) is a plan view looking from above the device, while FIG. **44**(*b*) is a cross section through line A—A in FIG. **44**(*a*).

In FIG. **44**, reference numeral **4406** is a vacuum container, reference numeral **4407** is an electrode I, reference numeral **4408** is a substrate, reference numeral **4409** is focus ring, reference numeral **4410** is a shower plate, reference numeral **4411** is an electrode II, reference numeral **4412** is a gas inlet, reference numeral **4413** is magnetic field applying means, reference numeral **4414** is a magnetic pump, reference numeral **4415** is a matching circuit I, reference numeral **4416** is a high frequency power supply I, reference numeral **4417** is a matching circuit II and reference numeral **4418** is a high frequency power supply II.

In the plasma device of FIG. **44**, a dipole ring magnet having a plurality of permanent magnets aligned in an annular shape are used as magnetic field applying means **4413**, as shown in the drawing. The permanent magnets constituting the dipole ring magnet are aligned so that a direction of magnetization passes through one rotation as the magnet positions go halfway round.

Gas introduced from the gas inlet **4412** is discharged into a process space from a plurality of small holes of the shower plate **4410**. This introduced gas, and reaction product gas discharged from a substrate surface, is expelled from a plurality of vacuum pumps **4414** to the outside via a space interposed between the magnetic field applying means **4413***a* and **4413***b* to the side of the substrate. A comparatively wide space is provided in an upper part of the vacuum pump **4414** so as to cause the gas conductance to be lowered. A projection surface of the upper section of the vacuum container **4406** is shown in FIG. **44**(*a*). The vacuum container **4401** has a shape close to a square, and four vacuum pumps **4402** are provided in the corners of this vacuum

container **4401**. In this way, if exhaust is carried out by a plurality of vacuum pumps aligned around the substrate substantially axisymmetrical to an axis perpendicular to the substrate surface and running through the center of the substrate, uniform gas flow can be realized in a rotational direction above the substrate, without causing hardly any lowering of gas conductance. That is, it becomes possible to cause a large amount of gas to flow up to a value close to the tolerance of the vacuum pump, and it is possible to handle an ultra high speed process for a large diameter substrate.

Here, the electrode II **4411** is a ring shaped metallic plate, and is provided so as to allow improvement of in-plane uniformity of plasma close to the surface of the substrate **4408**. High frequency power output from the high frequency power supply II **4418** is applied to the electrode II **4411** through the matching circuit II **4417**. If a balance of electron drift on the surface of the electrode II **4411** and the electron drift on the surface of the substrate **4408**, caused by a magnetic field applied by application of appropriate high frequency power to the electrode II **4411**, is obtained, plasma close to the surface of the substrate **4408** is made almost totally uniform. If uniformity of the plasma surface close to the surface of the substrate **4408** is good with application of high frequency to the electrode II **4411**, or if no problem arises even with nonuniformity, it is not particularly necessary to provide the electrode II **4411**.

In the plasma device of FIG. **43**, the shower plate **4305** is grounded, but it does not necessarily need to be grounded and it does not matter if a high frequency is applied. Also, it does not matter of a shower plate is not used and gas is discharged from another section.

FIG. **45** is a plan view showing an example of a plasma device of the present invention. Reference numeral **4501** is a vacuum container, reference numeral **4502** is a gas inlet, reference numeral **4503** is a magnetic field applying means, reference numeral **4504** is a gas outlet, and reference numeral **4505** is a gate valve. A surface of the vacuum container **4501** projecting from an upper part is approximately triangular in shape, and three vacuum pumps are placed in the corner sections. Other aspects of the plasma device are the same as the at described for FIG. **44**. With the plasma device of FIG. **45**, a distance between a gate valve **4505** and the substrate is smaller than in the plasma device shown in FIG. **44**. This is suitable for the case when the stroke of a substrate conveyance arm is restricted.

FIG. **46** is a plan view showing an example of a plasma device of the present invention. Reference numeral **4601** is a vacuum container, reference numeral **4602** is a gas inlet, reference numeral **4603** is magnetic field applying means, reference numeral **4604** is a gas outlet, and reference numeral **4605** is a gate valve. Two vacuum pumps are placed in the vacuum container **4602**. Apart from this, the plasma device is the same as that described in FIG. **44**. With the plasma device of FIG. **46**, similarly to the device of FIG. **45**, a distance between a gate valve **4505** and the substrate is smaller than in the plasma device shown in FIG. **44**. This is suitable for the case when the stroke of a substrate conveyance arm is restricted and when there is a margin in the expel capacity of the vacuum pump.

FIG. **47** is a plan view showing an example of a plasma device of the present invention. Reference numeral **4701** is a vacuum container, reference numeral **4702** is a gas inlet, reference numeral **4703** is magnetic field applying means, reference numeral **4704** is a gas outlet, reference numeral **4705** is a vacuum pump, and reference numeral **4706** is a gate valve. Two vacuum pumps are placed sideways in the vacuum container **4702**. Apart from this, the plasma device is the same as that described in FIG. **44**. The footprint of the plasma device including the vacuum container **4701** and the vacuum pump **4705** is larger, but the size of the vacuum container **4701** becomes a minimum. This is suitable for the case when the stroke of a substrate conveyance arm is restricted and when there are restrictions on the size of the vacuum container.

In the plasma device of FIG. **48**, a four vacuum pumps **4802** are respectively provided in each of upper and lower sections of the vacuum container **4801**, making eight vacuum pumps in total. In this way, if the number of vacuum pumps is increased, the load imposed on each vacuum pump is reduced and the vacuum pumps can be made smaller, which means that it is possible to make the footprint of the plasma device smaller. Remaining sections are the same as in the description for FIG. **44**.

The plasma device of FIG. **49** has comers of the upper section of the vacuum container **4901** rounded off. Within a space inside a vacuum container **4901** above the vacuum pump **4902**, unnecessary portions where gas flow is slow are reduced in size, which means that the atmosphere within the vacuum container **4901** is further purified.

FIG. **50** is a plan view showing an example of a plasma processing device of the present invention. Means for applying a magnetic field inside a container **5002** and **5004** are provided outside a vacuum container **5001**. Since the means **5002** and **5003** are divided top and bottom, the substrate can be conveyed without having to move an electrode I **5004** for mounting the substrate to be processed up and down. The plate type electrode I **5004** is parallel to a plate type electrode II **5005**, which is electrically grounded, and provided with a shower plate as means for introducing source material gas. Reference numerals **5006** and **5007** are means for expelling reaction product gas, and are configured so that the gas is discharged to the outside through a space formed between the magnetic field applying means **5002** and **5003**.

FIG. **51** is a plan view showing an example of a plasma processing device of the present invention. A plate type electrode I **5104** is parallel to a plate type electrode II **5105** which is connected to means **5108** for applying a high frequency independently of electrode I, and has a shower plate as means for introducing source material gas. Reference numeral **5106** and **5107** are means for expelling source material gas and reaction product gas to the outside.

FIG. **52** is a plan view showing an example of a plasma processing device of the present invention. An electrode I **5204** is provided, and there is a shower plate as means for introducing source material gas. Reference numerals **5206** and **5207** are means for expelling source material gas and reaction product gas, and are constructed to discharge gas to the outside.

The plasma device of FIG. **53** has a vacuum container **5301**, a source material gas inlet **5302** required to generate plasma inside the container, and a vacuum pump **5303** for expelling source material gas that has been introduced into the container. Part of a wall section constituting the container is a dielectric plate I **5304** formed of a material capable of transmitting microwaves with substantially no loss, and an antenna **5305** for radiating microwaves and an electrode I **5306** for mounting a substrate **5308** to be processed inside the container are provided outside the container, sandwiching the dielectric plate I. The microwave radiating surface of the antenna and a surface of the substrate that is to be plasma treated are arranged opposite each other and substantially parallel. Here, conveying of radiated

microwaves to the outlet side is prevented, and a reflector **5309** is preferably provided only above the substrate, for the purpose of causing uniform plasma generation.

Also, the electrode I for mounting the substrate can be grounded, or it is also possible to provide means for applying a d.c. bias or an a.c. bias. Further, in order to make introduction of source material gas uniform and to swiftly remove reaction product gas, the source material gas of this device is introduced from a plurality of small holes through a shower plate **5307** to a process space. This source material gas and reaction product gas are expelled to the outside by a plurality of vacuum pumps **5303**. A comparatively wide space is provided in an upper section of each vacuum pump so as not to cause lowering of the gas conductance. In this way, if gas is expelled from a plurality of vacuum pumps aligned substantially equal distances apart to the side of the substrate, it is possible to realize gas flow above the substrate uniform in a rotational direction without lowering the gas conductance hardly at all. That is, it becomes possible to cause a large amount of gas to flow close to the capacity of the vacuum pump, and it is possible to handle ultra high speed processing of large diameter substrates.

The plasma device of FIG. **54** is provided with two parallel plate type electrodes electrode I **5402** and electrode II **5403** inside the vacuum container **5401**. A gate valve **5404** and a substrate **5405** on which a film is to be deposited are respectively mounted on the electrode II and the electrode I. Source material gas is then introduced into the container, and matching circuit I **5406**, matching circuit II **5412**, high frequency power supply I **5408** and high frequency power supply II **5413** are connected for the purpose of applying high voltage to the electrode I and the electrode II. Means **5414** for applying a magnetic field to at least a target surface is provided outside the container. An auxiliary electrode A **5410** is provided at a region further out than the outer edge of the target for the purpose of making the density of plasma generated close to the surface of the target uniform. Means for adjusting a junction impedance provided at a portion electrically connected to the electrode II is attached to the auxiliary electrode A **5410**. At the region further out than the outer edge of the target, an auxiliary electrode B **5411** for applying a high frequency power separately and independently of a high frequency applied to the electrodes I and II is provided at a position separated from the substrate and electrode II, also for the purpose of making the density of plasma generated close to the surface of the target uniform. However, as an alternative to providing the auxiliary electrode B it is possible to employ a method for relieving plasma deviation caused by the magnetic field, by making the pressure inside the container at the time of plasma generation a high pressure (1—several tens of Torr). Further, even if the auxiliary electrode A or auxiliary electrode B is not provided, there is no need to specially provide the auxiliary electrode A and B in cases such as when in-plane uniformity of plasma close to the surface of the substrate is satisfactory, or where no problem occurs even with non-uniformity. The gas that has been introduced into the container passes through means **5414***a* and **5414**B for applying a magnetic field to the side of a substrate and is discharged to the outside from a plurality of vacuum pumps **5415**. At an upper portion of the vacuum pumps, there is provided a comparatively wide space so as to prevent lowering of the gas conductance. Also, it does not matter if the arrangement of the vacuum pumps is the same as that shown in FIG. **45**–FIG. **49**. It is also permissible to use another magnetic field applying means for applying the magnetic field. In this plasma device, plasma density is raised using a magnetic field, but there is no problem in using other means, and it is permissible to not use anything when there is no need to raise plasma density.

Still further, the electrode II being the electrode for holding the target can be divided into two equal halves, with a high frequency being respectively applied to the divided halves. However, the phases of the two high frequencies at this time are 180° out of phase with each other and it is necessary to provide means so that discharge does not occur between electrode Ia and electrode IIb. However this method is restricted to when the target is an insulating material, and when the target is conductive the substrate itself must be divided to match up with the electrode II. By using this method, since it becomes possible to keep the plasma potential low, the ion collision energy to the target can be reduced and it is confirmed that better quality films can be formed. It is also possible to use either of the following two methods as means of applying to the electrode II.

(a) FIG. **55** shows a first method. A high frequency power supply I **5504**, matching circuit I **5505**, high frequency power supply II **5506** and matching circuit II **5507** are connected to divided electrodes IIa **5501**, electrode IIb **5502**, for respectively applying a high frequency to the target **5503**, electrode IIa and electrode IIb, and the phases of the two high frequencies are made opposite and introduced by connecting a phase adjustment circuit **5508** to the electrode IIb side.

(b) FIG. **56** shows a second method. Reference numeral **5601** represents a divided electrode IIa. Reference numeral **5602** represents electrode IIb and reference numeral **5603** represents a target. High frequency oscillations from the high frequency power supply **5604** propagate to the matching circuit **5605** and are grounded through a balanced/non-equilibrium circuit (balance). Using this circuit, high frequency having mutually reversed phase is introduced.

(3) Taking FIG. **53** as an example, the plasma device of the present invention is provided with the exhaust space **5315** formed directly contacting the intake port **5314** of the vacuum port **5303**, to the side of the film forming space **5313** above a substrate **5308**.

By providing the exhaust space **5315**, being a comparatively wide space, to the side of the film forming space **5313**, source material gas that has been introduced from outside, or reaction product gas, is expelled without lowering the gas conductance, and it is possible to make a large amount of gas flow, close to the capacity of the vacuum pump.

This exhaust space **5315** is preferably provided at a number of places, and in this case the spaces are preferably arranged at positions symmetrical around the substantial center of the substrate **5308**. If a plurality of such spaces are symmetrically provided, the above described effects are even more remarkable.

The height b of the exhaust space **5315** is preferably as large as is practicable.

The width L of the exhaust space **5315** is preferably at least two times the height a of the film formation space **5313**. The uniformity of the gas flow is dramatically improved by the fact that the width L is two times the height a.

Embodiments

A plasma device of the present invention will be described in the following, with reference to the drawings, but the present invention is not limited to these embodiments.

(Embodiment 1)

In this embodiment, when plasma is generated by introducing microwaves into a container using the plasma device

shown in FIG. 1, the plasma stability is examined by varying the material of a member constituting an inner surface of the container, and the width of the member.

In FIG. 1, reference numeral **100** is a container capable of having its internal pressure reduced, reference numeral **101** is a chamber, reference numeral **102** is a first dielectric plate, reference numeral **103** is a waveguide dielectric plate, reference numeral **104** is an object to be treated, reference numeral **105** is plasma, reference numeral **106** is an antenna slot plate, reference numeral **107** is a coaxial tube, reference numeral **108** is an antenna guide, reference numeral **109** is an electrode, reference numeral **110** is a slot, reference numeral **201** is a radial line slot antenna, reference numeral **202** is a first O ring, reference numeral **205** is a space **3**, reference numeral **206** is a space **4** and reference numeral **207** is a space **5**.

In FIG. 1, the container capable of having the internal pressure reduced 100 comprises a chamber **101** (material: SUS), a first dielectric plate **102** (material: quartz), and first O ring **202** functioning as a seal between the chamber **101** and the dielectric plate **102**. The inside of the container **100** can be decompressed by an exhaust system, not shown, and the container **100** itself is electrically grounded.

A radial line slot antenna **201**, comprising the antenna guide **108** (material: Al), the antenna slot plate **106** (material: Cu) and the waveguide dielectric plate **103** (material: quartz), is located outside the container **100**. Microwaves are introduced into the antenna **201** through the coaxial tube **107** (material: Cu), conveyed in a radial direction while leaking out from each slot **110** provided in the antenna slot plate **106**, and radiated to the inside of the container **100**. Gas is made to flow into the container **100** from a source material gas supply system , not shown, and plasma **105** is excited. There is an electrode **109** having the function of holding an object to be treated **104** inside the container **100**, and the electrode **109** is located so that it is parallel to and opposite the antenna **201** and functions to heat the object to be treated. Also, the electrode **109** is capable of being made to move upwards and downwards from outside the container **100**, and the distance from the first dielectric plate **102** can be varied from approximately 10 mm to 60 mm.

FIG. 2 is a schematic plan view of the radial line slot antenna **201** shown in FIG. **1** looking from above. Hole sections (hereafter referred to as slots) **110** penetrating through antenna slot plate **106** are arranged in the slot plate, but the arrangement of the slots **110** is not limited to that shown in FIG. 2.

The slots **110** are configured having two slots **111***a* and **111***b* constituting a single pair, and the two slots in a pair are arranged at right angles to each other at a distance of a quarter of a wavelength λg of an incident wave passing through the coaxial tube **107** to the antenna **201**. The pairs comprised of a slot **11***a* and a slot **11***b*, namely the slots **110**, are each capable of outputting circularly polarized electromagnetic waves, and a plurality of slots **110** are numerously concentrically provided. Besides the concentric arrangement the slots **110** can also be arranged spirally. Although this embodiment is not limited to this concentric arrangement, the slots **110** are provided in this way so as to uniformly radiate electromagnetic waves within a large surface area.

The present invention is not limited to radiation of concentrically polarized electromagnetic waves, and it is possible to use linear polarization, but concentric polarization is preferred.

Reference numeral **107** is a coaxial tube for supplying microwaves to the antenna slot plate **106**, and is connected to a microwave power supply through a coaxial tube—waveguide converter, not shown, a waveguide and a matching circuit.

There is also a need for means for conveying the object to be treated **104** into and out of the chamber **101**, but this is omitted from FIG. **1**.

In this example, microwaves (frequency=8.3 GHz) are introduced to the radial line slot antenna **201** using the coaxial tube **107**, electromagnetic waves are radiated from the antenna **201** and plasma **105** is excited inside the space **5** of the chamber **100**. However, There was no excitation of plasma **105** within the space **5 (207)** with the SUS chamber **101**.

Accordingly, plating layers **(7)** comprising lead, tantalum, tungsten, aluminum, gold, copper and silver are coated on an inner surface of the SUS chamber **101** and the above described plasma ignition test was carried out. At this time, as the process gas Ar gas was used, and gas pressure was 500 mTorr.

FIG. **3** shows the results of the plasma ignition test. At this time, the thickness of the plating needs to be thicker than a skin depth determined from $d=(2/\mu_0\sigma\omega)^{1/2}$ of the microwaves, which means about 10 μm. From FIG. **3**, it is understood that if the specific conductivity of the material of the inner surface of the chamber **101** is made high, then it is easy for plasma excitation to take place. The results of this test show that at the instant microwaves are introduced into the container **100** the container starts to act as a resonator, and since a strong electric field is required in the plasma ignition test the q value of the resonator must be made high.

FIG. **4** shows results when an aluminum plating layer is provided on the inner surface of the SUS chamber **101** and a plasma ignition test is carried out by varying the thickness of the plating layer and the wavelength of microwaves introduced to the antenna **201**. From FIG. **4** it can be confirmed that at the time when the thickness of the aluminum plating layer is thicker than a skin depth of 1.67 μm determined from microwave $d=(2/\mu_0\sigma\omega)^{1/2}$, in the case of the frequency of the microwaves being 2.45 MHz, and that at the time when the thickness of the aluminum plating layer is thicker than a skin depth of 0.89 μm determined from microwave $d=(2/\mu_0\sigma\omega)^{1/2}$, in the case of the frequency of the microwaves being 8.3 MHz, plasma is stable.

Here, μ_0 is permeability of vacuum, σ is conductivity of the material in question, and ω is the angular frequency of the microwaves.

From the results described above, the following points become clear.

1) When the material of the member constituting the inner surface of the container is SUS, conductor loss is large and ignition is difficult.

2) By replacing the material of the member constituting the inner surface of the container for high conductivity material, the Q value of the resonator becomes comparatively high and the problem of difficult ignition does not arise.

3) When a material having conductivity of at least the conductivity of aluminum (3.7×10^7 [$\Omega^{-1}\cdot m^{-1}$]) is used as for the inner surface of the chamber **101**, the plasma becomes stable, and copper, gold, silver etc. are suitable as such as material.

A device incorporating the above results can be as shown in FIG. **5** and FIG. **6**. The device of FIG. **5** differs from the device in FIG. **1** in that an aluminium plating film **112** is coated to a thickness of 10 μm on the inner surface of the SUS chamber **101**. The device of FIG. **6** is different from the device of FIG. **1** in that it uses a plate member **113**

comprised of the above described material (having a thickness greater than the skin depth determined from the microwaves) and the inner surface of the chamber is covered. It can be confirmed that the devices of FIG. 5 and FIG. 6 are the same with respect to plasma stability.

(Embodiment 2)

In this embodiment, the device of FIG. **5** is different from embodiment 1 in that a metallic thin film **114** is provided at a vacuum seal region where the first dielectric plate **102** (material: quartz) contacts a first O ring **202**, as shown in FIG. **7**, and the first O ring is not exposed to electromagnetic waves radiated from the antenna slot plate **106**. Fluorine type resin is used as the material for the first O ring.

FIG. **8** is an enlarged view of region A in FIG. **7**, and shows the case where the metallic thin film **114** is provided at a vacuum seal region where the first dielectric plate **102** (material: quartz) contacts a first O ring **202**.

When the first O ring is made of a material such as resin that absorbs microwaves, it is directly heated by electromagnetic waves radiated from the antenna slot plate **106*m*** as a result of discharge over a long time and it will be understood that damage will occur.

Therefore, metallic thin films each having a thickness of 10 μm and respectively being aluminium, nickel, and copper are provided at the vacuum seal region where the first dielectric plate **102** contacts the first O ring **202**, as the metallic thin film **114**. This thickness of 10 μm was validated in embodiment 1, and is a thickness value larger than the skin depth determined from microwave $d=(2/\mu O\sigma\omega)^{1/2}$ that can sufficiently reflect microwaves. A durability test of the first O ring **202** was carried out using a device provided with this type of metallic thin film **114**. The results showed that when nickel (conductivity: 1.4×10^6 [$\Omega^{-1}\cdot m^{-1}$]) was used, conductivity was low so microwaves were not sufficiently reflected, the power of the microwaves was subject to heat loss and the first O ring was excessively heated and damaged after a discharge time of 2–3 hours. On the other hand, in the case where a comparatively high conductivity material such as aluminum (conductivity: 3.7×10^7 [$\Omega^{-1}\cdot m^{-1}$]) or copper (conductivity: 6.0×10^6 [$\Omega^{-7}\cdot m^{-1}$]) was used, damage to the first O ring could not be confirmed even after a discharge time of 100 hours.

Consequently, it has been found that the metallic film **114** should have high conductivity and high adhesion to the first dielectric plate **102**. It also goes without saying that it is necessary for the thickness of the metallic thin film **114** to be thicker than the skin depth determined from microwave $d=(2/\mu_0\sigma\omega)^{1/2}$.

FIG. **9** is an enlarged view of region A in FIG. **7** and shows the case where in place of the metallic thin film **114** the first O ring **202** itself is coated with a metallic thin film **115** having the same function as the metallic thin film **114** provided in the first dielectric plate **102**. In this way, by also coating the first O ring **202** itself with the metallic thin film **115** the same effects as for the device of FIG. **8** can be obtained. Also in the case where the first O ring **202** is made of metal, the above problem is solved.

(Embodiment 3)

In this embodiment, as shown in FIG. **10**, a device provided with a second dielectric plate **116**, having a gas inlet **117** for supplying desired gas in a substantially uniform manner provided between the first dielectric plate **102** and the electrode **109** for holding the object to be treated **104**, was used, and the uniformity of plasma **105** generated in the space 2 (**109**) was examined.

FIG. **10** shows the device incorporating the results of the second embodiment, and aluminum (Al) was coated to a thickness of 10 μm as a metallic thin film **114**, at a region for vacuum sealing where the first dielectric plate **102** comes into contact with the first O ring **202**. AlN (aluminium nitride) was used as the second dielectric plate **116** shown in FIG. **10**. Since aluminium nitride contains nitrogen, it is characterized by the fact that there is less discharge gas compared to quartz.

In the device of FIG. **10**, Ar gas was introduced into space 1 (**208**) as a plasma gas, and uniformity of plasma **105** generated in the space 2 (**209**) as a result of introducing microwaves to the antenna **201** was evaluated in order to study the ion saturation current density. At this time, the gas pressure of the space 2 (**209**) was 50 mTorr, and the power of microwaves input to the antenna **201** was 1600 W.

FIG. **11** is a graph showing the results of studying saturated electron current density. In FIG. **11**, the mark ■ represents the case when the second dielectric plate **116** having the gas inlet **117** is provided, the mark ● represents the case where the second dielectric plate **116** is not provided, and the mark ▲ represents the case where the second dielectric plate **116** is provided without the gas inlet **117**.

From FIG. **11** is will be understood that by providing the second dielectric plate **116** having the gas inlet **117** the plasma is made uniform. In the case where the gas inlet **117** is not provided (mark ▲) there is no reaction accelerator for causing plasma excitation inside the container [namely the space 2 (209)), which obviously means that there will be no plasma excitation.

By providing this type of second dielectric plate **116** it is possible to supply source material gas uniformly onto a surface of an object to be treated **104** having a diameter greater than 300 mm which was impossible in the related art, and it is also possible to uniformly remove generated reaction by-product gas from the object to be treated **104**.

With the above described second dielectric plate **11 6**, gas inlets **117** are arranged so that there are an equal number per unit surface area, but this arrangement is not limiting and it is possible to arrange them as conditions demand.

(Embodiment 4)

In this embodiment, the plasma device of FIG. **10** is provided with a metallic thin film **214** at a region for vacuum sealing where the second dielectric plate **116** (material: aluminium nitride) comes into contact with the second O ring **216**, and the effect of preventing the second O ring **216** being exposed to electromagnetic waves radiated from the antenna slot plate **106** was evaluated. Aluminium (Al) having a thickness of 10 μm was used as the metallic thin film **214**, and fluorine type resin was used as the second O ring **216**.

FIG. **13** is an enlarged view of region B in FIG. **12**.

Apart from this point, embodiment 4 is the same as embodiment 2.

Similarly to embodiment 2, the extent of damage to the second O ring **216** was evaluated. These results show that in the case where the metallic thin film **214** is provided, similarly to the case where the metallic thin film **114** of embodiment 2 is provided, there was no damage to the second O ring **216** even after a discharge time of 100 hours.

Also, similarly to the first O ring **202** shown in FIG. **9**, the second O ring **216** shown in FIG. **10** can be itself covered with a metallic thin film **115** having a similar function to the **114** provided on the second dielectric plate **116**, and it was confirmed that this had the same effect as when the above described metallic thin film **214** was provided.

(Embodiment 5)

With this embodiment, in the plasma device of FIG. **12** materials having a different dielectric loss angle are used as

the first dielectric plate 102, and the density (ion saturation current) of plasma generated in the space 2 (209) was evaluated.

As materials having a different dielectric loss angle for constituting the first dielectric plate 102, Bakelite (BM-120, dielectric loss aangle=0.044), glass (corning #0010 dielectric loss aangle=0.006), AlN (dielectric loss aangle=0.001), and SiO_2 (dielectric loss aangle=0.0001) were used. At this time, the material constituting the second dielectric plate 116 was AlN.

Apart from this point, embodiment 5 was the same as embodiment 2.

FIG. 14 is a graph showing results of measuring the ion saturation current. It will be understood from FIG. 14 that since electrical loss becomes small and microwave power is supplied to the container without loss with decrease in the dielectric loss angle tan δ, the plasma density(ion saturation current) increases. Particularly, it will be understood that when a material having dielectric loss angle tan δ of less than 10^{-3} is used as the first dielectric plate 102, it is possible to obtain plasma having a high ion saturation current of 12 mA/cm^2. This means that it is preferable to have a material with a lower dielectric loss angle tans as the material for the first dielectric plate 102, for example, quartz (SiO_2) or aluminium nitride (AlN) having tan δ of less than 10^{-3}.

(Embodiment 6)

With this embodiment, in the plasma device of FIG. 12 materials having a different dielectric loss angle are used as the second dielectric plate 116, and the density (ion saturation current) of plasma generated in the space 2 (209) was evaluated.

As materials having a different dielectric loss angle for constituting the second dielectric plate 116, Bakelite (BM-120, dielectric loss angle=0.044), glass (corning #0010 dielectric loss angle=0.006), AlN (dielectric loss angle= 0.001), and SiO_2 (dielectric loss angle=0.0001) were used. At this time, the material constituting the second dielectric plate 116 was quartz.

Apart from this point, embodiment 6 was the same as embodiment 5.

Substantially the same effects as in FIG. 14 are also obtained with this embodiment. That is, it can be understood that when a material having a dielectric loss angle tan δ of less than 10^{-3} is used for the second dielectric plate 116, plasma having a high ion saturation current of greater than 12 mA/cm^2 can be obtained.

However, there is a need to provide gas inlets 117 in the second dielectric plate 116, and a requirement to use a material with satisfactory manufacturing precision. Accordingly, it is possible to use quartz (SiO2) or aluminium nitride (AlN) having tan δ of less than 10–3 as the material of the second dielectric plate 116, but it is preferable to use aluminium nitride (AlN) from the point of view of manufacturing precision.

(Embodiment 7)

With this embodiment, in the plasma device shown in FIG. 15, in order to study conditions where plasma excitation does not take place in the space 1 (208) between the first dielectric plate 102 and the second dielectric plate 116, the following experiment was carried out.

FIG. 15 is a drawing in which pressure P1 of the space 1 (208), pressure P2 of the space 2 (209) and the distance tg between the first dielectric plate 102 and the second dielectric plate 116 have been added to the drawing showing the device of FIG. 12.

FIG. 16 is a schematic drawing of a jig used to observe whether or not there is plasma excitation in the space 1 (208). The jig of FIG. 16 is located directly below the first dielectric plate 102 (material: quartz) being part of the container 100 of the plasma device in FIG. 1. In FIG. 16, reference numeral 301 is an upper glass plate, reference numeral 302 is a lower glass plate, reference numeral 303 is a middle glass plate, reference numeral 304 is a space 6, reference numeral 305 is a tungsten wire, and reference numeral 306 is an aluminium wire coated with ceramics.

The jig of FIG. 16 has two glass plates (301 and 302) of 2 mm in thickness fixed a distance tg apart. A side section of the space 6 (304) formed by the two glass plates (301 and 302) is covered by a separate glass (303) so that plasma does not penetrate inside the space 5 of width tg. Since the inside of the space 6 (304) is not airtight, gas penetrates and the pressure inside the space 6 (304) becomes almost the same as the pressure inside the container.

In order to confirm whether or not plasma is generated inside the space 6 (304), two probes (305*a* and 305*b*) are inserted into the gap. The probes (305*a* and 305*b*) are tungsten of diameter 0.1 mmϕ and length 8 mm. The probes (305*a* and 305*b*) are heated if they are irradiated with microwaves, so the outer surface of glass at the edges of the probes (305*a* and 305*b*) was sealed with copper plate (not shown in the drawing). A variable voltage was applied between the two probes (305*a* and 305*b*) in an electrically floating state, and the current flowing was measured using a multimeter.

FIG. 17 is a graph showing a relationship between probe voltage and probe current observed when the variable was applied between the two probes (305*a* and 305*b*). The curve (a) of FIG. 17 shows the a current voltage characteristic that is symmetrical to the left and right in the case where plasma was generated inside the space 6 (304). On the other hand, the curve (b) of FIG. 17 indicates only a noise component in the case where plasma is not generated in the space 6 (304). However, since they are many cases where plasma generated inside the space 6 (304) is unstable, it is not always possible to obtain the current voltage characteristic having good symmetry as shown in FIG. 17. Therefore, in a case where the current value is observed to exceed 10^{-7} A, even only slightly, it is generally judged that plasma has been generated in the space 6 (304).

In this embodiment, plasma ignition tests were carried out for 6 different conditions by combining the cases where the distance tg between the two glass plates (301 and 302) was 0.7 mm and 4 mm, and where the microwave frequency was 2,45 GHz, 5.0 GHz and 8.3 GHz. At this time, Ar gas was introduced so that the pressure inside the space 6 (304) was 0.1–10 Torr. Also, the microwave power was supplied up to a maximum of 1600 W.

Table 1 shows the results of the plasma ignition tests for the above described 6 conditions. In the table, the mark O indicates that plasma was not generated inside the space 6 (304) and the mark x indicates that plasma was generated inside the space 6 (304).

TABLE 1

	Microwave frequency [GHz]		
Tg [mm]	2.45	5.0	8.3
0.7	X	○	○
1.4	X	X	X

As shown in table 1, in the set of cases where the distance between the two glass plates (301 and 302) [namely the width of the space 6 (304)] tg is 0.7 mm and the microwave

frequency is 5.0 GHz or 8.3 GHz, even if microwave power was delivered up to 1600 W (power density 1.27 W/cm^2) there was no plasma excitation inside the space **6** **(304)**. On the other hand, in the other cases it was confirmed that there was plasma excitation.

FIG. **18** shows results of studying the relationship between minimum discharge power and Ar pressure for the four conditions where plasma is not generated, among the six conditions described above. From FIG. **18**, it will be understood that in the case where the microwave frequency is low (for example 2.45 GHz), even if the width tg of the space **6** **(304)** is narrowed down to 0.7 mm, plasma excitation occurs inside the space **6** **(304)** at low power.

Contrary to this, by making the microwave frequency high (for example 5.0 GHz), and narrowing the width tg of the space **6** **(304)** to 0.7 mm or less, even if microwave power is delivered up to 1600 W (power density 1.27 W/cm^2) plasma is not excited inside the space **6** **(304)**.

Accordingly, in the plasma device shown in FIG. **15**, in order to stop plasma excitation in the space **1** **(208)** between the first dielectric plate **102** and the second dielectric plate **116**, microwave frequency input to the antenna is made at least 5.0 GHz, and the width of the space **1** **(208)** is made 0.7 mm or less.

Also, in the plasma device shown in FIG. **15**, when a pressure **1** **(P1)** of the space **1** **(208)** between the first dielectric plate **102** and the second dielectric plate **116**, and a pressure **2** **(P2)** of space **2** **(209)** surrounded by the second dielectric plate **116** and wall sections (chamber) **101** of the container other than the second dielectric plate **116**, and where an electrode **109** for holding the object to be treated **104** is arranged, have the relationship **P1>P2**, it was confirmed that plasma excitation did not occur in the space **1** **(208)**. Particularly, it is understood that when **P1** is sufficiently high compared to **P2**, for example when there was a pressure difference of about 10 times, these effects were more remarkable.

Accordingly, by providing means **5** for generating a pressure difference so that the pressure **1** **(P1)** of the space **1** becomes higher than the pressure **2** **(P2)** of the space **2** **(209)** it is possible to prevent plasma excitation in the space **1** **(208)**.

(Embodiment 8)

With this embodiment, in the plasma device shown in FIG. **15**, the effects were studied of either reducing in size, shielding, or not providing at all, those slots, among slots (hole portions penetrating the slot plate) provided in the slot plate constituting the antenna, arranged at sections where the density of plasma generated in the space **2** **(209)** is locally high.

FIG. **19** is a schematic cross sectional drawing showing the slot plate when a shielding plate **119** is provided on the slots **110'** positioned close to the center of the slot plate. FIG. **20** is a schematic plan view showing the slot plate when the size of the slots **110'** positioned close to the center of the slot plate is reduced. FIG. **20**(*b*) is an enlarged view of region A of FIG. **20**(*a*).

In FIG. **20**, the case is shown where the length is shortened for only two rings of slots from the center of the slot plate, but reduction in size of the lots can be realized by, for example, shortening the slot length.

FIG. **21** shows results of studying the density of plasma generated at the space **2** **(209)**, using the slot plate shown in FIG. **19**. In FIG. **21**, slot A, slot B and slot C are the names respectively given to the slot distributions for the case when the shielding region is small, the case where the shielding region is intermediate in size, and the case where the shielding region is large. From FIG. **21** it will be understood that with slot A, the density of plasma at the center of a measuring electrode is raised. By arranging the shielding plate **119** at this portion so that slot distribution is slot B, it can be expected to make the plasma density uniform. However, if the shielding region is made wider, as in slot C, conversely to slot A the plasma density rises at the outer edge of the electrode.

Accordingly, by providing a shielding plate **119** having an appropriate shielding region, the output of electromagnetic waves radiated from the slots is reduced, and the density of excited plasma can be made even more uniform.

A shielding plate **119** that can hope to achieve the above describe operation and effect preferably has a shape and size so as to shield the slots of the slot plate. Namely, it goes without saying that either by reducing the slot size or even using a method of not providing any slots, the same effects can be anticipated as in the case where the slots are shielded.

(Embodiment 9)

With this embodiment, in the plasma device shown in FIG. **15**, the effects were studied of providing means **6** for maintaining the antenna at a fixed temperature close to the antenna, and means **7** for maintaining the temperature of the first dielectric plate at a fixed temperature close to the first dielectric plate.

In the plasma device shown in FIG. **15**, as shown in FIG. **22**, structures **120** and **121** capable of maintaining the antenna guide **108**, waveguide dielectric plate **103**, antenna slot plate **106**, and first dielectric plate **102** at a fixed temperature are provided close to the antenna guide **108**. The structures **120** and **121** are equivalent to the means **6** and the means **7**.

In this case, the antenna slot plate **106** is arranged so as to be completely stuck to the waveguide dielectric plate **103**. By having this arrangement, if a gap exists between the antenna slot plate **106** and the waveguide dielectric plate **103**, surface waves will be generated at that part, and it is possible to effectively avoid a phenomenon where it is impossible to radiate electromagnetic waves. To do this, the shape of the waveguide dielectric plate **103** must hardly be changed by forces or heat from outside, and it is necessary to use a material having high thermal conductivity and low microwave loss, for example, quartz glass (SiO_2), aluminium nitride (AlN) etc., but it is not limited to these materials, and any material can be used as long as it satisfies the above described conditions.

In this embodiment, in the two structures **120** and **121**, a method is employed where heating medium flows and desired locations are cooled, but a material having high thermal conductivity is preferred as the heating medium. As such a heating medium, fluid, gas (helium, nitrogen, etc.) and the like can be considered, but they are not limiting.

(Embodiment 10)

As shown in FIG. **23**, this embodiment is different from embodiment 9 in that a spacer **118** is provided in a space between the antenna slot plate **106** and the first dielectric plate **102** as means for preventing warping of the slot plate. In this embodiment the spacer **118** is made of TEFLON.

In the case where it is impossible prevent warping of the slot plate in embodiment 9, by providing the spacer **118** in a space between the antenna slot plate **106** and the first dielectric plate **102** it becomes possible to prevent warping of the antenna slot plate **106**.

The spacer **118** is provided at a position where the slots **119** of the slot plate **106** do not open out so as not to impede radiation of electromagnetic waves from the slot plate **106**.

(Embodiment 11)

As shown in FIG. **24**, this embodiment differs from embodiment 9 in that a sensor **122** is provided either in the container or at the edge of the container, as means **9** for detecting the presence or absence of generated plasma in the space 2.

The sensor **122** is connected to a microwave power supply, not shown in the drawing, and when plasma is being excited in the chamber **101** it detects plasma, causes the microwave power supply to provide output and plasma excitation is inhibited, while when plasma is disappearing the sensor **122** immediately suspends output from the microwave power supply. In this embodiment, a photo transistor is used as the sensor **122**, and detects plasma light emission, but it is perfectly acceptable to use alternate means.

Accordingly, by adopting the sensor **122** it is possible to prevent careless heating and damage of the inside of the chamber **101** and the object to be treated **104** etc due to magnetic waves radiated from the antenna **201** when plasma activation suddenly stops.

(Embodiment 12)

In this embodiment, the effects of having a structure for causing the temperature of the container wall surface and parts other than the object to be treated inside the container to be raised to 150° C., and/or a structure for causing the temperature inside all the units constituting the exhaust system to be raised to 150° C.

The above described effects were studying a relationship between container inner wall temperature and reaction by-product (polymerization film) deposition, namely, dependence of deposited film thickness on inner wall temperature using the vacuum device shown in FIG. **25** in a range of 50–150° C.

In FIG. **25**, reference numeral **501** is a chamber, reference numeral **502** is plasma, reference numeral **503** is an object to be treated, reference numeral **504** is an electrode, reference numeral **505** is a heater, reference numeral **506** is a laser, and reference numeral **507** is a photodetector. In this case, gas used was a mixture of C_4F_8 and H_2O, [C_4F_8:H_2O= 7:3, total gas flow amount:40 (sccm)], pressure was 10 mTorr, and discharge power was 1000 W. With the vacuum device of FIG. **25**, an Si wafer was used attached to a flat tip of a copper rod, as the object to be treated **503**, and heating of the object to be treated was carried out using a sheath heater provided inside the rod.

FIG. **26** shows the results of studying the relationship between the deposition rate of the polymerization film and the temperature of the inner wall of the chamber. From FIG. **26** it will be understood that the polymerization film deposition rate is rapidly decreased accompanying increase in wafer temperature and that at around 150° C. deposition of the polymerization film could not be observed.

Accordingly, it was determined that by providing either a structure for causing the temperature of the container wall surface and parts other than the object to be treated inside the container to be raised to **150°** C., and/or a structure for causing the temperature inside all the units constituting the exhaust system to be raised to 150° C., it was possible to prevent the build up of a polymerization film composed of moisture and reaction by-products.

(Embodiment 13)

As shown in FIG. **27**, this embodiment differs from embodiment 9 in that a Xenon (Xe) lamp is used as means for heating the object to be treated **104**.

The Xe lamp **125** can effectively heat only the surface of the object to be treated **104** by irradiating light to the object to be treated **104** through a light inlet **124** and a window **123** made of a material that passes light.

In this embodiment a Xe lamp is used as means for heating the object to be treated **104**, but another light source can be used, or the electrode **109** holding the object to be treated **104** can be heated by a direct electrothermal line etc., but heating using Xe lamp irradiation is preferred.

Also, in FIG. **27** the Xenon lamp inlet **124** is provided on part of the outside of the chamber **101**, but it is more preferable to uniformly provide a plurality of such inlets on the outside of the chamber **101**.

(Embodiment 14)

A simple schematic drawing of the situation when adopting a staged cooler method in the collection and recycling of fluorocarbon gas is shown in FIG. **28**. It is possible to carry out recycling of the gas expelled from inside the container as a liquid by gradually cooling from a high boiling point gas and performing liquefaction and distillation purification. Fluorocarbon gas contributes to global warming 100,000–1, 000,000 times more than CO_2, which means that the effects of collecting and recycling the fluorocarbon gas is immense.

(Embodiment 15)

A self cleaning gas plasma has to satisfy the following two requirements in order to rapidly remove reaction gas products adhered to the chamber without inflicting damage on the inner wall of the chamber.

① high ion density and radical density

② low plasma potential (small energy of ions incident to the chamber wall)

Also, at the same time as these two requirements, there is also a demand for material of the inside of the chamber to have strong ion radiation and extremely good plasma resistance.

FIG. **29** shows the relationship between average binding energies of various fluorine type gases and their plasma parameter. From this drawing, it will be more clearly understood that there is an intimate relationship between binding energy and plasma parameter. Namely, ion irradiation energy becomes small and ion density becomes high as binding energy falls. Plasma energy does not depend largely on binding energy of gas molecules. From this it will be understood that NF_3 is an extremely suitable gas for self cleaning. Accordingly, when a self cleaning structure is required the inner walls of the container must have excellent plasma resistance and it is best to use an alloy such as AlF_3/MgF_2.

FIG. **30** shows the results of evaluating damage caused by plasma irradiation of AlF_3/MgF_2 alloy when is used as the chamber inner wall material of the device of FIG. **15**, and gas having a small gas molecule binding energy (such as NF3) is used as cleaning gas. FIG. **30**(*a*) is a profile of the AlF_3/MgF_2 alloy in a depth direction using XPS (X ray photoelectron spectroscopy) before NF_3 plasma irradiation, and FIG. **30**(*b*) is a profile after two hours of NF_3 plasma irradiation. From the results shown in FIG. **30**, it will be understood that there is hardly any damage attributable to plasma irradiation.

Accordingly, when there is a need to have a self cleaning structure in the device the container inner walls must have excellent plasma resistance and it is best to use AlF_3/MgF_2 alloy.

(Embodiment 16)

With this embodiment, in the plasma device of FIG. **15** an antenna **201** is located outside the container **101** via the first dielectric plate **102**, and plasma excitation is caused by introducing microwaves through a coaxial tube **107** and radiating electromagnetic waves inside the container **101**.

FIG. **31** is a graph showing the results of measuring distribution of ion saturation current, FIG. **32** is a graph

showing the results of measuring distribution of electron temperature, and FIG. **33** is a graph showing the results of measuring distribution of electron density.

From FIG. **31** to FIG. **33** it will be understood that with the plasma device of the present invention, uniform plasma excitation can be caused by covering high density plasma having a ion saturation current of at least 14 mA/cm^2, electron density in the region of 1 .eV (15000 K) and electron density of at least 10^{12} over a large surface area of diameter 300 mm or more inside the container **101**.

FIG. **34** is a schematic drawing of a system for measuring the ion current distribution. This is measurement of ion current distribution using a disk-shaped electrode **401**. The disk-shaped electrode **401** was used in place of the object to be treated **104** and electrode **109** in the plasma device shown in FIG. **15**.

In FIG. **34**, reference numeral **401** is the disk-shaped plate, reference numeral **402** is a pin, reference numeral **403** is an aluminium wire, reference numeral **404** is a resistor, reference numeral **405** is an operational amplifier, reference numeral **406** is an A-D converter, reference numeral **407** is a computer, reference numeral **408** is a stepping motor and reference numeral is a power supply.

The disk-shaped electrode **401** in FIG. **34** is a piece of disk-shaped aluminium having a diameter of 300 mmϕ and nine pins **402** are embedded in the top of the disk-shaped electrode **401** an equal distance apart on a line running from the center to a point at a radius of 140 mm.

Electric current flowing from the plasma to the pins **402** is taken outside the chamber through ceramics-coated aluminium wires **403** connected to the pins **402** and current introduction terminals (not shown). A voltage of −20V relative to the potential of the chamber is applied to the pins **402**, and only positive ions flow in the plasma. A potential generated by this positive ion flow is converted to a voltage signal by the resistor **404**, and after being amplified by the operational amplifier **405** is converted to a digital signal by the 16 channel A-D converter **406** and transmitted to the computer **407**.

The aluminium electrode **401** is covered with polyimide tape (not shown). Measurements of rotation of the electrode **401** by the stepping motor **408**, and measurements of ion current by the A-D converter are synchronized using the computer **407**. Measurement of ion current is carried out 200 times for each pin **402** per rotation of the electrode **401**, to obtain a fine two dimensional distribution.

FIG. **35** is a schematic diagram showing a single probe system used in measurement of electron temperature and electron density in this example.

If the probe is inserted into a section where the microwave power density is large, as shown in FIG. **35**, the probe tip (tungsten wire, 0.1 mmϕ) **601** is heated by the microwaves, and there is a possibility that thermoelectrons will be discharged. There is also a possibility that ionization will occur frequently inside the probe seal. In either case it becomes impossible to obtain a voltage current characteristic of an ordinary single probe.

Therefore, 0.5 mm diameter silver wire **602** wound in a spiral manner is arranged clearing a gap at the edge of the probe tip **601** for the purpose of shielding microwaves. The silver wire has low resistance and is not heated by the. Also, the use of comparatively fine wire for shielding is so that the effect on the plasma can be kept to a minimum.

A comparison was carried out for the case where the silver wire was provided in a spiral manner, and the case where it was not. At a section where the microwave power density was small, hardly any difference could be seen between the two characteristics. At a section where the microwave power density was large, in the case where the silver wire was not arranged in a spiral manner, when a negative potential was applied to the probe the current value was noticeably increased, but in the case where the silver wire was arranged in a spiral manner a normal characteristic was obtained. In this way, in the case where microwave power density inside the plasma is large, it is effective to shield the edge of the probe tip **601** from microwaves using a metallic wire etc.

In order to obtain a z direction [in the device of FIG. **15** a direction from the second dielectric plate **116** facing the electrode **401**] distribution for each plasma parameter, a structure was made that could move the probe in the z direction using the stepping motor **408**. The maximum speed of movement of the probe was 300 mm/sec and the positional resolution was 0.02 mm. control of probe position using the stepping motor **408** and measurement of the current voltage characteristic was synchronized using the computer **497**. In order to prevent heating of the probe, experimentation was carried out restricting the time of reciprocation in the z direction to less than 5 seconds.

(Embodiment 17)

With this embodiment, plasma etching was carried out for the object to be treated **104** by applying a high frequency to the electrode **109** having the function of holding the object to be treated **104**, in the plasma device shown in FIG. **15**. An Si wafer formed in the surface of a Poly-Si film mainly used as a gate electrode material for a MOS transistor was used as the object to be treated **104**, and this Poly-Si film was etched.

A high frequency was applied to the electrode **109** having the function of holding the object to be treated **104** from means (not shown) capable of applying a high frequency bias. Gas such as Cl_2, O_2, HBr etc was used as the source material gas, but this is not limiting. FIG. **36** is a graph showing results of the plasma etching. From FIG. **36**, for a total of nine measurement points (the center point and 8 points spaced equally apart in two rings of four 150 mm and 280 mm from the center) on the object to be processed (size 300 mmϕ), with an etching rate uniformity of the Poly-Si film of about 5% per unit time, it was confirmed that extremely uniform etching was possible on a large diameter (300 mmϕ) object to be treated.

(Embodiment 18)

In this embodiment the case where the device of the present invention is applied to a plasma oxidation device for oxidizing the surface of an object to be treated at low temperature is illustrated. Here, description will be given for the case where an Si substrate was used as the object to be processed, the and a gate oxidation film was formed on the surface of the object to be treated using direct oxidation with O_2.

Ar and O_2 were used as source material gases. It is also possible to use Xe in place of Ar as a carrier gas. It is also possible to add He etc. to a mixed gas comprising Ar and O_2.

FIG. **37** is a schematic diagram showing a combination of a cross section of elements constituting this example, and a system for measurement of element withstand voltage.

In FIG. **37**, the element whose withstand voltage has been measured comprises an object to be treated **701** constituted by an n type Si wafer, a field oxidation film **702**, a gate oxidation film **703**, and a gate electrode **704**. Also, reference numeral **705** is a probe used in measurement of withstand voltage, reference numeral **706** is a voltmeter, reference numeral **707** is voltage applying means and reference numeral **708** is an ammeter.

Formation of the element shown in FIG. **37** and measurement of the withstand voltage are carried in the following order.

(1) After a field oxidation film **702** (thickness: 800 nm) formed of SiO_2 has been formed on the n type Si wafer using a thermo oxidation method [(H_2+O_2 gas), H_2=1 l/min, O_2=1 l/min, temperature of object to be treated=1000° C.], part of the field oxidation film **702** was subject to etching processing and the surface of the n type Si wafer was exposed.

(2) Only the exposed surface of the field oxidation film **702** was directly oxidized using the plasma device of the present invention, and the SiO_2 gate oxidation film **703** (surface area 1.0×10^{-4} cm^2, thickness 7.6 nm) was formed. The film forming conditions at this time were film forming gas (Ar+O_2), gas pressure 30 mTorr, partial pressure ratio Ar:O_2=98:2, microwave power 700 W, oxidation processing time 20 min, the object to be treated was held in an electrically floating state, and the temperature of the object to be treated was 430° C.

(3) A gate electrode **704** of Al (thickness 1000 nm) was formed on the field oxidation film **702** and the gate oxidation film **703** by a vapor deposition method.

(4) The probe **705** was brought into contact with the gate electrode **704**, a d.c voltage was applied to the object to be treated **701** formed of the n type Si wafer via the gate electrode **704**, and the voltage at which the gate oxidation film **703** suffered dielectric breakdown (namely the withstand voltage) was measured using the voltmeter **706**.

FIG. **38** is a graph showing the results of measuring withstand voltage. FIG. **38**(*a*) shows the case when the gate oxidation film is manufactured using the device of the present invention. On the other hand, FIG. **38**(*b*) shows the case when. the gate oxidation film is manufactured using a device of the related art. With a conventional device, plasma is generated by applying a high frequency of 100 MHz to parallel plate type electrodes, and the gate oxidation film is formed.

In FIG. **38**, the horizontal axes represent withstand voltage and the vertical axes represent the frequency with which elements were obtained for each withstand voltage. For example, the bar graph at the 10 MV/cm part of the horizontal axis is the frequency of occurrence of elements having withstand voltage in the range 9.5–10.4 MV/cm. The number of elements measured was 30 for each of FIG. **38**(*a*) and FIG. **38**(*b*).

The following points become clear from FIG. **38**.

1 Elements manufactured using the device of the related art have a wide withstand voltage distribution (that is, uniformity is bad) and average withstand voltage is 10.2 MV/cm [FIG. **38**(*b*)].

2 Elements manufactured using the device of the present invention have a narrow withstand voltage distribution (that is, uniformity is good) and a high average withstand voltage of 11.9 MV/cm can be obtained, so it is understood that the film quality of the gate oxidation film has been improved [FIG. **38**(*a*)].

Accordingly, by carrying out direct oxidation using the plasma device provided with the radial line slot antenna of the present invention, it is possible to form an oxidation film having high uniformity and high withstand voltage, which means that it was confirmed that elements having excellent withstand voltage could be manufactured stably.

In this example, the device of the present invention has been applied to a plasma oxidation device for oxidizing the surface of an object to be treated at a low temperature, but it was also confirmed that it was possible to obtain high uniformity oxidation films by applying it to a plasma nitriding device for nitriding the surface of an object to be treated.

(Embodiment 19)

This example shows an embodiment for the case where the present invention is applied to a plasma CVD device for film formation of a thin film on the surface of a substrate. Description will be given for the case where single crystalline Si is formed as a film on an amorphous Si substrate.

In the example, film formation of single crystalline Si is carried out on an amorphous Si substrate, but it is also possible to form polycrystalline Si as a thin film on amorphous Si. The material of the substrate on which film formation is carried out is not limited to Si and can be a glass or quartz substrate, etc.

SiH_4, H_2, and Ar are used as the source material gas, but the source material gas is not limited to this combination and it is possible to use Xe in place of Ar, although Xe is preferred.

The proportion of Ar must be maintained at at least half of the total amount. In this example, Ar is provided in a proportion of 50%, but this is not limiting. The reason for this is that on a plasma excitation method using microwaves, since it is necessary to have a quite high electron density within the plasma in order to maintain excitation of the plasma, it is necessary to increase the proportion of Ar that can obtain a higher electron density.

Also, the amorphous Si substrate surface is heated up to a temperature of 500° C. by irradiation by a xenon lamp and an insufficient energy is compensated for by plasma ion irradiation. It is also possible to use other temperature raising methods, but the method using a xenon lamp is preferred.

In order to form a film of single crystalline Si on the amorphous Si substrate, it is necessary for the kernel of crystal Si grown on the substrate surface during film formation to have the same in-plane orientation as the substrate. This means that if differences exist in the film in-plane formation conditions, film formation will be carried out with unequal orientation of the crystal kernel, so there is a necessity to make in-plane film formation conditions exactly uniform.

By using the plasma device of the present invention, it is possible to provide uniform film formation conditions over a large surface area, and for the first time it becomes possible to form a film of single crystalline Si on an amorphous substrate at low temperature, which was impossible in the related art.

As a result, it was possible to form a single crystalline Si film on a Si substrate of 300 mm in diameter at a temperature of 500° C. and a film formation rate of 0.1 μm every minute.

Results of forming a film of Poly-Si on a glass substrate also show that it is possible to obtain a high quality thin film with a mobility (carrier transfer rate) of 300 or greater.

(Embodiment 20)

This example is different from embodiment 19 in that a film of SiO_2 is formed on the Si substrate, and the remaining aspects are the same and will be omitted.

In this example, SiH_4, O_2 and Ar are used as the source material gas, but this combination of gases is not limiting and it is possible to use Xe in place of Sr as a carrier gas, and N_2O can be used instead of O_2. It is also possible to add He etc, to the mixed gas comprising SiH_4, O_2 and Ar.

As a result, it was possible to form a film on an Si substrate of 300 mm in diameter at a temperature of 350° C. and a film formation rate of 0.1 μm every minute and in-plane uniformity was less than ±5%.

(Embodiment 21)

This example is different from embodiment 19 in that a film of Si_3N_4 is formed on the Si substrate, and the remaining aspects are the same and will be omitted.

In this example, SiH_4 and NH_3 are used as the source material gas, but this combination of gases is not limiting

and it is possible to use Xe in place of Ar, and N_2 can be used instead of NH_3.

As a result, it was possible to form a film on a Si substrate of 300 mm in diameter uniformly at room temperature and with a film formation rate of 0.1 μm every minute, and in-plane uniformity was less than ±5%.

(Embodiment 22)

This example is different from embodiment 19 in that a BST thin film [(Ba, Sr) TiO_3], being a ferroelectric thin film, is formed on a Pt thin film that has been formed on the Si substrate. The remaining aspects are the same as embodiment 19 and will be omitted.

In this example, $Ba(DPM)_2$, $Se(DPM)_2$, and $TiO(O\text{-}iC_3H_7)_2$ and Ar are used as the source material gas, but this combination of gases is not limiting and it is possible to use Xe in place of Sr, although it is preferable to use Xe rather than Ar.

The Pt thin film is formed on the Si substrate beforehand using a sputtering method, and also serves as barrier metal to prevent the electrode and the Si substrate against reaction with a foundation of Ba, Sr, Ti. This embodiment is not limited to the Pt thin film, and it is also possible to use Ru or RuO_2 etc.

As a result, it was possible to achieve a film formation rate of **0**.5mm every minute uniformly on a Si substrate of 300 mm in diameter at a temperature of 450° C., and the relative permittivity of the thin film was approximately 160.

(Embodiment 23)

This example is different from embodiment 19 in that a SBT thin film [$SrBi_2Ta_2O_9$] is formed on a Pt thin film that has been formed on the Si substrate. The remaining aspects are the same as embodiment and will be omitted.

In this example, $Sr(DPM)_2$, $Bi(C_6H_5)_3$, $TiO(O\text{-}iC_3H_7)_2$ and Ar are used as the source material gas, but this combination of gases is not limiting and it is possible to use Xe in place of Sr, although it is preferable to use Xe rather than Ar.

As a result, a ferroelectric thin film having a remanence of about 30 $\mu m/cm^2$ was obtained.

(Embodiment 24)

This example shows the case where the present invention is applied to a plasma CVD device for formation of a diamond thin film on the surface of a substrate. Description will be given for the case where Si is used as a substrate and film formation is carried out on this substrate.

In this example CO, H_2, O_2 and Ar are used as the source material gas, but this combination is not limiting.

The substrate temperature was set to 500° C. Also, the diamond thin film was formed by simultaneously proceeding with the elementary reactions of decomposition and deposition of carbon gas, diamond nucleation, generation of sp^3 carbon, and removal of by-products (graphite type carbon, polymer). In the formation of the diamond thin film, ion energy must be low, and compared to a plasma device of the related art the device of the present invention enables plasma generation over a large surface area at high density and low energy, which means that film formation rate can be increased and high quality thin film formation is possible.

(Embodiment 25)

This example is different from embodiment 19 in that a P-SiN film is formed on the Si substrate, and the remaining aspects are the same as embodiment 19 and will be omitted.

In this example, the substrate temperature was 300° C. and SiH_4, NH_3 and Ar were used as the source material gas, but this combination of gases is not limiting and it is possible to use Xe in place of Sr, and to replace NH_3 with N_2.

As a result, it was possible to form a film on a Si substrate of 300 mm in diameter at a film formation rate of 0.1 μm every minute and in-plane uniformity was less than ±5%.

(Embodiment 26)

This example is different from embodiment 19 in that a P-SiO film is formed on the Si substrate, and the remaining aspects are the same as embodiment and will be omitted.

In this example, the substrate temperature was 300° C. and SiH_4, N_2O and Ar were used as the source material gas, but this combination of gases is not limiting and it is possible to use Xe in place of Sr.

As a result, it was possible to form a film on a Si substrate of 300 mm in diameter at a film formation rate of 0.1 μm every minute and in-plane uniformity was less than ±5%.

(Embodiment 27)

This example is different from embodiment 19 in that a BPSG film is formed on the Si substrate, and the remaining aspects are the same as embodiment 19 and will be omitted.

In this example, the substrate temperature was 450° C. and SiH_4, PH_3, B_2H_6, O_2 and Ar were used as the source material gas, but this combination of gases is not limiting and it is possible to use Xe in place of Sr.

As a result, it was possible to form a film on a Si substrate of 300 mm in diameter at a film formation rate of 0.1 μm every minute and in-plane uniformity was less than ±5%.

(Embodiment 28)

This example shows the case where the device of the present invention is applied to a plasma nitriding device for nitriding the surface of an object to be treated at low temperature. Description will be given for the case where an Si substrate is used as the object to be treated and direct nitriding is carried out on the surface of the Si substrate using N_2. The source material gas was Ar and N_2. It is also permissible to use He or Xe in place of Ar as a carrier gas. Also, He, Ne, Xe etc. can be added to the mixed gas comprising Ar and N_2. It is also possible to replace N_2 with NH_3.

FIG. **39** is a graph showing results of analyzing the chemical binding state of a Si surface, using an X-ray photoelectron spectroscope, after direct nitriding of the Si substrate surface for 30 minutes using a mixed gas of Ar/N_2=97%/3% and growth of a 5 nm nitride film, using the device of the present invention. The horizontal axis represents binding energy between photoelectrons and a nucleus, and the vertical axis represents the number of electrons having that binding energy. For the sake of comparison, the spectrum of the surface of 5 nm silicon nitride film grown by processing in an N_2 atmosphere at 1300° C. for 120 minutes is also shown.

From FIG. **39** a peak attributable to the silicon substrate and a peak of the silicon nitride film grown on the substrate were confirmed in the spectrum for the silicon nitride film grown using the device of the present invention. From the fact that the position and shape of the peak attributable to the silicon substrate were almost the same as those for the silicon nitride film formed at 1300° C., it was confirmed that the formed silicon nitride film was complete.

FIG. **40** is a schematic drawing showing a combination of a cross section of an element formed in the present embodiment and a system for measuring dielectric breakdown injection charge amount for the element. In FIG. **40**, the element that has had dielectric breakdown injection charge amount measured comprises an object to be treated **801** made of an n type Si wafer, a field oxidation film **802**, a gate nitride film **803** and a gate electrode **804**. Also, reference numeral **805** is a probe used in measurement of dielectric breakdown injection charge amount, reference numeral **806** is a voltmeter, reference numeral **807** is a constant current source and reference numeral **808** is an ammeter.

Element formation and dielectric breakdown injection charge amount measurement shown in FIG. **41** are carried

out using the measurement meter shown in FIG. **40** and carrying out the following procedure.

(1) After a field oxidation film **802** (thickness: 800 nm) formed of SiO_2 has been formed on the n type Si wafer **801** using a thermo oxidation method [(H_2+O_2 gas), H_2=1 l/min, O_2=1 l/min, temperature of object to be treated=1000° C.], part of the field oxidation film **802** was subject to etching processing and the surface of the n type Si wafer was exposed.

(2) Only the exposed surface of the field oxidation film **802** was direct nitrided using the plasma device of the present invention, and the gate nitride film **803** (surface area 1.0×10^{-4} cm^2, thickness 5.6 nm) formed of Si_3O_4 was formed. The film forming conditions at this time were film forming gas ($Ar+N_2$), gas pressure 30 mTorr, partial pressure ratio Ar/N_2=99.7%–90%/0.3%–10%, microwave power 700 W, nitriding processing time 30 min, the object to be treated was held in an electrically floating state, and the temperature of the object to be treated was 430° C.

(3) A gate electrode **804** of Al (thickness 1000 nm) was formed on the field oxidation film **802** and the gate nitride film **803** by a vapor deposition method.

(4) The probe **805** was brought into contact with the gate electrode **804**, a constant current was applied to the object to be treated **801** formed of the n type Si wafer via the gate electrode **804** using the constant current source **807** so the electron density became 200 mA/cm^2, and time taken for the gate nitride film **803** to suffer dielectric breakdown was measured. The electron density value multiplied by this time is the dielectric breakdown injection charge amount.

FIG. **41** is a graph showing results of measuring the dielectric breakdown injection charge amount of a silicon nitride film formed at 430° C. using the device of the present invention. For the sake of comparison, the dielectric breakdown injection charge amount for a silicon nitride film formed at 1300° C. in an N_2 atmosphere is also shown. In FIG. **41** the horizontal axis represents injection charge amount and the vertical axis represents the cumulative frequency of elements obtaining each of the charge injection amounts. Twenty elements were measured. From FIG. **41** it is understood that in the case of forming a nitride film on an Si substrate using the device of the present invention, even at a film formation temperature as low as there was no effect (With normal film formation at 430° C. it is impossible to even cause direct nitriding on the surface of a silicon substrate. In order to carry out nitriding of a silicon surface using N_2 gas a substrate of at least 1000° C. is required.), a maximum dielectric breakdown injection charge amount of 123 C/cm^2 was obtained, and the same characteristic as that for dielectric breakdown injection charge amount for a film formed at 1300° C. was exhibited.

Accordingly, by carrying out direct nitriding of a silicon surface using the device of the present invention, formation of a silicon nitride film having the same electrical characteristic as a silicon nitride film formed at 1300° C. was achieved even at a low temperature of 430° C.

In this embodiment, the device of the present invention has been applied to a plasma nitriding device for nitriding the silicon surface of an object to be treated at low temperature, this embodiment is not limited to Si and even if it was applied to nitriding of metallic surfaces such as Ta, W, Al, Ti etc it was confirmed that it was possible to obtain a high quality metallic nitride film at a low substrate temperature.

(Embodiment 29)

This embodiment shows an example where the device of the present invention is used as a plasma CVD device for forming a polycrystalline silicon thin film on the surface of a substrate, and formation of a polycrystalline silicon film on an oxidation film that has been formed on the Si substrate. The source material gas was a mixed gas of Ar and SiH_4. It is also permissible to add H_2, He, Ne, Xe etc. to the mixed Ar and SiH_4 gas. It is also possible to use He or Xe in place of Ar. It is also possible to use Si_2H_6, $SiHCl_3$, SiH_2Cl_2 and $SiCl_4$ instead of SiH_4 and obtain the same effects. An oxidation film formed on the Si substrate to a thickness of 50 nm using a thermal oxidation method [(H2+O2) gas, H2=1 l/min, O2=1 l/min, Si substrate temperature=1000° C.] is used as the substrate. In this embodiment, formation of the oxidation film is carried out using a thermal oxidation method, but the means for oxidation film formation is not thus limited and an oxidation film formed by any means is permissible. After formation of the oxidation film on the Si substrate, and after a polycrystalline silicon thin film has been deposited to a thickness of 120 nm using the device of the present invention under conditions of substrate temperature 300° C. and Ar/SiH_4=99.95%/0.05%, the polycrystalline silicon thin film is analyzed using an X-ray diffractometer. For the sake of comparison, after a polycrystalline silicon thin film has been deposited to a thickness of 120 nm using a parallel plate type CVD device of the related art under conditions of substrate temperature 300° C. and Ar/SiH_4=99.95%/0.05%, the polycrystalline silicon thin film was similarly analysed using an X-ray diffractometer.

FIG. **42** is a graph showing X-ray diffractometer measurement results of the polycrystalline silicon thin films. The horizontal axis represents an X-ray scattering angle 2θ attributable to the surface direction, and the vertical axis represents the X-ray strength at that scattering angle. A large peak strength of the X-ray diffractometer indicates a high cystallinity in the surface direction. From FIG. **42** it will be understood that the polycrystalline silicon film formed using the device of the present invention clearly has improved cystallinity compared to the film formed using the parallel plate type CVD of the related art.

(Embodiment 30)

This embodiment shows the case where the present invention is applied to a magnetron plasma etching device.

A plasma device has two plate type electrodes electrode I and electrode II which are parallel to each other. A substrate to be processed using plasma is mounted on a isurface of electrode I opposite to electrode II, and is provided with means for applying a magnetic field being horizontal and unidirectional onto the substrate. The electrode II comprises a central section electrically connected to ground, and an outer section connected to a high frequency power supply that can be controlled independently of a high frequency power supply connected to the electrode I. A focus ring is also provided at a section electrically connected to electrode I, for the purpose of making the density of plasma generated around the substrate surface uniform. The focusing ring has means for adjusting junction impedance.

A structural drawing of the etching device of the present invention is the same as FIG. **44** and so is omitted.

In this device, a dipole ring magnet (hereinafter referred to as a DRM) having a plurality of permanent magnets lined up in an annular shape is used as the magnetic field applying means. The permanent magnets constituting the DRM are aligned so that magnetization is performed in one direction as the magnet positions go halfway round.

Here, a DRM is used as the magnetic field, but other means for applying a magnetic field can also be used. Also, the plasma density is increased here using a magnetic field, but other means can also be used, and when there is no need to increase plasma density there is no need to use any means at all.

The electrode II is a ring shaped metallic plate in this case, and is provided in order to cause increased in-plane uniformity of the plasma in the vicinity of the substrate surface. High frequency power output from the high frequency power supply II is applied to the electrode II via the matching circuit II. By balancing electron drift on the surface of the electrode II, caused by application of a magnetic field using application of a suitable high frequency power to the electrode II, and electron drift on the surface of the substrate, the plasma in the vicinity of the substrate is made almost completely uniform. In a case where the in-plane uniformity of the plasma is favourable even without the application of a high frequency to the electrode II, or where there is no problem even if it is not uniform, there is no need to specially provide the electrode II. Similarly, also with respect to the focus ring provided for the purpose of making the density of the plasma to be generated in the vicinity of the substrate surface uniform, in a case where the in-plane uniformity of the plasma is favourable even without the application of high frequency to the electrode II, or where there is no problem even if it is not uniform, it is possible to either reduce the size of the focus ring or not provide it at all.

As a material for the wall surface inside the container, a material containing as low an amount of discharge gas (such as moisture) as possible is used, in this case AlN. However, the internal wall surface is not limited to this material. The high frequency applied to the electrode I was 13.56 MHz, and the high frequency applied to the electrode II was 100 MHz. In this case, by making the frequency applied to the electrode II higher than the frequency applied to the electrode I, a self bias voltage for the electrode II becomes small which means that the problem of the electrode II being sputtered by the plasma and the inside of the container suffering from metallic contamination are solved. The high frequencies applied to the electrodes I and II are not limited to those in this example.

Only the exhaust system of the above described device was modified and the major difference of the exhaust system of the present invention was evaluated in comparison to the exhaust system of the related art (i.e., the method disclosed in FIG. **43**(*a*)). The evaluation method was to prepare an insulation film BPSG to a thickness of 1.5 μm on an Si wafer 200 mm in diameter as the substrate to be plasma processed, mount the substrate on electrode I and carry out etching while increasing a total gas flow amount with a fixed process gas ratio, and measuring the etching rate using disparity between the exhaust systems. The conditions for etching the substrate were power of a high frequency (13.56 MHz) applied to the electrode I 1700 W, power of a high frequency (100 MHz) applied to the electrode II 400 W, process pressure 40 mTorr, electrode spacing 10 mm, and process gas ratio of C_4F_8:5%, CO:15%, Ar 78%, and O_2:2%, but these conditions are not limiting. The results of the evaluation are shown in FIG. **57**. (The marks ▲and Δrepresent etching rate at the center of the wafer, while the marks ■ and □ represent etching rate at the end of the wafer.) From these results the following point becomes clear.

(1) In the case of adopting the exhaust system of the present invention, it is understood that it is possible to obtain a higher etching rate and uniformity than with the exhaust system of the related art.

Also, BPSG is formed on a Si wafer of 200 nm in diameter to a thickness of 1.5 μm as the substrate, 0.7 μm of mask material referred to as resist was coated on this substrate, and after carrying out exposure and developing processing a hole pattern of diameter 0.1 μm was formed on

the mask material. This substrate was etched under the same conditions as the above described experiment, and after etching hole formation was observed. As a result, the following point becomes clear.

(2) Reaction by-products clogging up the holes are effectively expelled due to improved exhaust rate and increased process gas flow amount, which makes it possible to obtain favourable hole formation. Compared to a taper angle of 86° for an exhaust system of the related art, a taper angle of 89° and ideal formation are possible with the exhaust system of the present invention. Here, taper angle means the angle formed by the Si wafer and the side wall of the hole (refer to FIG. **58**).

(Embodiment 31)

This embodiment shows the case where the present invention is applied to a magnetron sputtering device.

The structure of this device is the same a FIG. **54**, so a further drawing is omitted. Here, a target is the substrate **5404** to be plasma processed mentioned in FIG. **54**. A dipole ring magnet having a plurality of permanent magnets aligned in a ring shape is used as magnetic field applying means, but this is not limiting. Material of the inner walls of the container are a material discharges a little discharge gas (such as moisture) as possible, so it is AlN in this case. However, high frequency power applied to the electrode I was 43.0 MHz, the frequency applied to the electrode II was 13.56 MHz, and the frequency applied to the auxiliary electrode B was 100 MHz. The high frequencies applied to the respective electrodes are not limited to those described above, but the frequency applied to the auxiliary electrode B is preferably set high so that the self bias potential for electrode B is low and sputtering of the auxiliary electrode B itself can be avoided.

Only the exhaust system of the above described device was modified and the major difference of the exhaust system of the present invention was evaluated in comparison to the exhaust system of the related art (exhaust system in one direction only, i.e., the method disclosed in FIG. **43**(*a*)). Evaluation was carried out by generating plasma using Ar as carrier gas under a pressure of 10 mTorr, carrying out sputtering, measuring the distribution of cut away amount of the Al target, and comparing the state of plasma generated in the vicinity of the target. A single crystalline Si wafer (6 inches) was used as the substrate to be subjected to film formation.

The results of this evaluation are shown in FIG. **59**. From these results the following point becomes clear.

(1) In this embodiment, by increasing the gas flow amount when the pressure inside the container is 10 mTorr to 1.5 sccm, the in-plane uniformity of the cut away amount is improved. This is considered to be due to the fact that a uniform exhaust rate and gas flow are realized in the vicinity of the target.

Al was used as the target, but the same results were also confirmed with Cu.

(Embodiment 32)

This embodiment shows the case where the present invention is applied to a plasma oxidation device for oxidizing the surface of a substrate at low temperature in a plasma device using a radial line slot antenna capable of uniformly supplying gas in a large flow amount.

The structure of this device is the same as FIG. **53**, and so a further drawing will be omitted.

Description will be given for the case where an Si wafer is used as the substrate and a gate oxidation film is formed by direct oxidation of the Si wafer surface using O_2, Ar and O_2 are used as the source material gas. It is also possible to

use Xe instead of Ar as a carrier gas. It is also possible to add He etc. to the mixed gas comprising Ar and O_2.

FIG. **60** is a schematic diagram showing a combination of a cross section of an element formed with this embodiment, and a system for measuring withstand voltage of the element. In FIG. **60**, the element whose withstand voltage was measured comprises a substrate **4001** formed of an n-type Si wafer, a field oxidation film **4002**, a gate oxidation film **4003**, and a gate electrode **4004**. Also, reference numeral **4005** is a probe used in measurement of the withstand voltage, reference numeral **4006** is a voltmeter, reference numeral **4007** is voltage applying means, and reference numeral **4008** is an ammeter.

The formation and withstand voltage measurement of the element shown in FIG. **60** was carried out through the following sequence of events. After a field oxidation film **4002** (thickness: 800 nm) comprising SiO_2 has been has been formed on the n-type Si wafer using a thermal oxidation method [(H_2+O_2) gas, H_2=1 l/min, O_2=1 l/min, temperature of object to be processed=1000° C.] part of the field oxidation film **4002** is subjected to etching processing and the surface of the n-type Si wafer **4001** is exposed.

Only the exposed surface of the n-type Si wafer **4001** was subjected to direct nitridation using the plasma device of the present invention to form the gate oxidation film **4003** (surface area=1.0×10^{-4} cm^2) formed of SiO_2. The film formation conditions at this time were: film formation gas $(Ar+O_2)$; gas pressure 30 mTorr; partial pressure ratio $Ar:O_2$=98%:2%; microwave power 700 W; oxidation processing time 20 minutes; the substrate was held in an electrically floating state and the temperature of the object to be processed was 430° C. However, the film formation conditions are not thus limited.

A gate electrode **4004** (thickness 1000 nm) formed of Al was formed on the field oxidation film **4002** and the gate oxidation film **4003** using a vapor deposition method.

The probe **4005** was brought into contact with the gate electrode **4004**, a d.c. voltage was applied to the object to be processed **40001** formed of the n-type Si wafer, through the gate electrode **4004**, and the potential at which the gate oxidation film **4003** suffered dielectric breakdown (namely, withstand voltage) was measured using the voltmeter **4006**.

FIG. **61** is a graph showing the results of measuring withstand voltage. FIG. **61**(*a*) shows the case of a gate insulation film formed by with the device of the present invention, while FIG. **61**(*b*) shows the case of a gate insulation film formed by with the device of the related art.

FIG. **62** shows a plan view of a plasma device using a radial line slot antenna having the exhaust system of the related art. The only difference from a device using the exhaust system of the present invention is the exhaust system. The exhaust system of the present invention has a comparatively wide space provided above the vacuum pump, and expulsion in carried out from a plurality of vacuum pumps arranged spaced substantially equal distances apart at the side of the substrate, it is possible to have a gas flow uniformly above the substrate in a rotational direction substantially without lowering the gas conductance. Specifically, it becomes possible to cause a large amount of gas to flow up to the capacity of the vacuum pump, and it is possible to handle ultra high speed processing of a large diameter substrate. Conversely, because the exhaust system of the related art uses vacuum pump expulsion in only one direction, the space above the vacuum pump is narrow and the gas conductance is lowered, it is not possible to realize uniform gas flow above the substrate. As a result, it is not possible to make a large amount of gas flow and it is impossible to handle high speed processing of a large diameter substrate.

In FIG. **61**, the horizontal axis represents withstand voltage and the vertical axis represents frequency of occurrence of elements that obtained each withstand voltage. For example, the bar graph of the horizontal axis 10 MV/cm is the frequency of occurrence of elements having a withstand voltage in the range 9.5–10.4 MV/cm. The number of elements measured was 30 in each of FIGS. **61**(*a*) and **61**(*b*). From FIG. **61** the following point becomes clear.

Elements formed using the device provided with the exhaust system of the related art have a wide distribution of withstand voltage (namely bad film quality uniformity), and an average withstand voltage of 10.3 MV/cm [FIG. **61**(*b*)].

Elements formed using the device of the present invention have a narrow distribution of withstand voltage (namely good film quality uniformity), and a high average withstand voltage of 11.5 MV/cm can be obtained, which means that the film quality of a gate oxidation film is improved [FIG. **61**(*a*)].

FIG. **63** is a graph showing distribution of film thickness of the inner surface of wafer surface of the Si oxidation film. The horizontal axis represents distance from the center of the wafer and the horizontal axis represents film thickness of the direct oxidation film., The film thickness of the direct oxidation films formed with the device provided with the exhaust system of the related art has low uniformity. On the contrary, the film thickness of direct oxidation films formed with the device of the present invention are almost constant at the wafer surface, and uniformity is high. Accordingly, since it is possible to form oxidation films having high uniformity and high withstand voltage it was confirmed that it was possible to stably manufacture elements having excellent withstand voltage.

In this embodiment, the device of the present invention has been applied to a plasma oxidation device for oxidizing a Si surface of a substrate at low temperature, but it is not limited to a Si surface and it was confirmed that it was also possible to obtain oxidation films having high uniformity with metallic surfaces.

(Embodiment 33)

This embodiment shows the case where the present invention is applied to a plasma nitriding device for nitriding the surface of a substrate at low temperature in a plasma device using a radial line slot antenna capable of uniformly supplying gas in a large flow amount.

The structure of this device, as well as the plasma device using a radial line slot antenna provided with the exhaust system of the related art, are the same as embodiment 3, and so will be omitted.

Similarly to embodiment 3, a Si wafer is used at the substrate, and description will given for the case where the surface of the Si wafer is subjected to direct nitridation using N_2, and a gate nitridation film is formed.

FIG. **64** is a schematic drawing showing a combination of a cross section of an element formed in the present embodiment and a system for measuring dielectric breakdown injection charge amount for the element. In FIG. **64**, the element that has had dielectric breakdown injection charge amount measured comprises an object to be treated **5001** made of an n type Si wafer, a field oxidation film **5002**, a gate nitride film **5003** and a gate electrode **5004**. Also, reference numeral **5005** is a probe used in measurement of dielectric breakdown injection charge amount, reference numeral **5006** is a voltmeter, reference numeral **5007** is a constant current source and reference numeral **508** is an ammeter. Element formation and dielectric breakdown

injection charge amount measurements shown in FIG. **64** were carried out using the following procedure.

After a field oxidation film **5002** (thickness: 500 nm) formed of SiO_2 has been formed on the n type Si wafer **5001** using a thermo oxidation method [(H_2+O_2 gas), H_2=1 l/min, O_2=1 l/min, temperature of object to be treated=1000° C.], part of the field oxidation film **5002** was subject to etching processing and the surface of the n type Si wafer was exposed.

Only the exposed surface of the field oxidation film **5002** was direct nitrided using the plasma device of the present invention, and the gate nitride film **5003** (surface area 1.0×10^{-4} cm^2, thickness 5.6 nm) formed of Si_3O_4 was formed. The film forming conditions at this time were film forming gas (Ar+N_2), gas pressure 30 mTorr, partial pressure ratio Ar/N_2=99.7%–90%/0.3%–10%, microwave power 700 W, nitriding processing time 20 min, the object to be treated was held in an electrically floating state, and the temperature of the object to be treated was 430° C. However, the film formation conditions are not thus limited.

A gate electrode **5004** of Al (thickness 1000 nm) was formed on the field oxidation film **5002** and the gate nitride film **5003** by a vapor deposition method.

The probe **5005** was brought into contact with the gate electrode **5004**, a constant current was applied to the object to be treated **5001** formed of the n type Si wafer via the gate electrode **5004** using the constant current source **5007** so the electron density became 100 mA/cm^2, and time taken for the gate nitride film **5003** to suffer dielectric breakdown was measured. The electron density value multiplied by this time is the dielectric breakdown injection charge amount.

FIG. **65** is a graph showing the results of measuring the dielectric breakdown injection charge amount.

In FIG. **65**, the horizontal axis represents injection charge amount, and the vertical axis represents the frequency of occurrence of elements obtaining each injection charge amount. The number of elements measured was 20 in each of the related art method and the present invention. From FIG. **65** the following point becomes clear.

In the elements manufactured using the device of the related art, distribution of injection charge amount was wide (namely film quality was bad), and average charge injection amount was 59.3 C/cm^2.

In the elements manufactured using the device of the present invention, the distribution of injection charge amount was narrow (namely film quality was good) and it was possible to obtain a high average load injection amount of 572 C/cm^2, so it will be understood that film quality of the gate oxidation film was improved.

FIG. **67** is a graph showing results of measuring the barrier function of the direct oxidation film. Si wafers that have been subjected to direct oxidation using a device provided with the exhaust system of the related art and a device provided with the exhaust system of the present invention were bleached for five hours in a 100% O_2 atmosphere at 600° C., and then measured using an X-ray photoelectron spectroscope. In FIG. **67**, the horizontal axis represents the time for which the Si wafer subjected to direct oxidation was bleached in the O_2 atmosphere, and the vertical axis represents the peak surface area of SiO_2 that has been chemically shifted by oxidation of the surface. From the drawing, the following point becomes clear.

With the surface of the Si wafer subjected to direct oxidation using the device of the related art, the peak surface area increases with time, and it is oxidized in the O_2 atmosphere with passage of time. From this it will be understood the direct oxidation film formed using the device of the related art has a low barrier function against oxygen.

With the surface of the Si wafer subjected to direct oxidation using the device of the present invention, there is no increase in peak surface area with time, and it is not oxidized in the O_2 atmosphere with passage of time. From this it will be understood the direct oxidation film formed using the device of the present invention has a high barrier function against oxygen.

FIG. **68** shows the relationship between amount of oxygen and carbon included within the direct oxidation film formed from the film formation atmosphere, and total flow amount of process gas. From the drawing the following point becomes clear.

As the total flow amount of process gas increases, the amount of oxygen and carbon included within the formed direct oxidation film decreases, and it becomes possible to form a direct oxidation film having low oxygen and carbon contamination. This means that the device of the present invention enables film formation while there is a large flow amount of gas, and so is suitable for the formation of direct oxidation films having low oxygen and carbon contamination.

Accordingly, by carrying out direct oxidation using the plasma processing device of the present invention, it is possible to suppress the concentration of impurities within a film, and to form an oxidation film having high film quality uniformity and high injection load amount, with uniform distribution of film thickness, and a high barrier properties, and so it was confirmed that it was possible to stably manufacture elements having excellent characteristics.

Also, in this embodiment, the device of the present invention has been applied to a plasma oxidation device for oxidizing the Si surface of a substrate at low temperature, but it is not limited to an Si surface and it was confirmed that it was possible to obtain metallic oxidation films with high uniformity if applied to oxidation of a metallic surface such as Ta, W, Al, Ti, etc.

(Embodiment 38)

This embodiment shows a case where the device of the present invention is applied to a plasma CVD device for forming a diamond film on a substrate, in a plasma device using a radial line slot antenna capable of uniformly supplying a large gas flow amount.

The structure of this device is the same as that of embodiment 3, and so will be omitted.

A diamond thin film has excellent mechanical, electrical thermochemical and optical characteristics, and is mostly noted for the fact that its semiconductor characteristics can be controlled by adding appropriate impurities.

In this embodiment, the case will be described where a thin diamond film is formed for the intention of application to a mask, for use in X-ray lithography anticipated as the next generation manufacturing technology for ULSI silicon.

FIG. **69** shows a structural example of a mask for use with an X-ray diffractometer. A circuit pattern for transcribing is formed in an absorber of a central square section of the drawing. A parallel beam X-ray is incident from a substrate side, and X rays pass through a part of the central square section where there is no absorber and are projected onto to a Si wafer to be subject to pattern formation, not shown in the drawings, located on the absorber side. The diamond thin film utilized as a support layer for the absorber must be transparent, have a smooth surface and have uniform characteristics at the inner surface.

In this embodiment, formation of a diamond thin film on a Si wafer has been illustrated. In the following, the method will be described.

An Si substrate from which surface contaminants (particles, organic matter, metal) and a natural oxidation film

have been removed is introduced into a chamber. After loading, the diamond thin film is formed to a thickness of 1–2 μm using the aforementioned device. First of all, the surface of the Si substrate is subjected to carbonization processing in an $Ar/H_2/CH_4$ or $Ar/H_2/CO_2$ atmosphere, and then the Si substrate is negatively biased and a diamond crystal kernel is generated on the Si substrate. After this processing, a diamond thin film is formed to a thickness of 1–2 μm in a $Ar/H_2/CH_4/O_2$ or $Ar/H_2/CO_2/O_2$ atmosphere. It is possible to replace Ar with Xe. The chamber pressure at the time of processing is 3–500 mTorr, process gas flow amount can be made up to 3SLM, and the Si wafer is temperature controlled to 300–700° C. With the device of the present invention, it is possible to generate high density and uniform plasma over a large surface area, and by providing a shower plate the supply of source material gas is made uniform and it is possible to uniformly form a film on a large diameter substrate. Also, by narrowing the processing space and uniformly and rapidly expelling a large flow amount of process gas it is possible to rapidly remove reaction by-products, which means that reaction by-products such as non diamond components that have been uniformly etched by atomic hydrogen are rapidly expelled and a high quality diamond film can be generated.

Results of evaluating the diamond thin film formed to a thickness of 2 μm in the Si wafer are shown in Table 2.

TABLE 2

Results of Diamond Film Evaluation	
film thickness, inside 4 inch wafer (total ellipsometric film thickness)	2.00 ± 0.01 μm
Surface roughness	5 nm
permeability (measurement after removal of Si substrate)	90% at 633 nm

Permeability was measured after the central section of the rear surface (the opposite side to the surface on which the thin film was formed) of the Si wafer was removed to expose the diamond thin film. The measurement system is shown in FIG. **70**.

FIG. **71** shows variation of surface roughness and permeability when the total flow amount of process gas was changed. In the related art, machine polishing was carried out after film formation. By using the plasma device of the present invention, reaction by-products such as non diamond components that have been uniformly etched by atomic hydrogen are rapidly expelled and a high quality diamond film can be generated.

(Embodiment 39)

This embodiment shows a case where the present invention is applied to a magnetron sputtering device.

A structural drawing of this embodiment is the same as that for embodiment 31 and so will be omitted. As described in embodiment 5, amorphous Ta_4B can be applied as a absorber material of a mask for X-ray lithography. As described in embodiment 5, after a flat thin diamond film has been formed, a film of Ta_4B is continuously formed using a cluster tool, without coming into contact with the atmosphere in a clean room at all.

A characteristic of the cluster tool is that by connecting between each process chamber using an Ar or N_2 tunnel, thin film formation can be carried out continuously under an extremely pure atmosphere without exposing the semiconductor, metal, or insulator on the wafer to the atmosphere at all. Also, each process chamber achieves an ultra high vacuum state of the ultimate vacuum of 10^{-10} Torr, but at the time of conveying the wafer, a number of mTorr to several tens of Torr is maintained using very pure Ar or N_2, and contamination of the wafer surface by organic matter or moisture etc. is prevented. Further, conveyance between each cluster is carried out using a port encapsulated with N_2 or dry air, and wafer cleansing and lithographic processing is also carried out in an N_2 or dry air atmosphere, so that it is possible to carry out processing that completely excludes all sorts of impurity elements from the atmosphere.

In this embodiment, formation of an amorphous Ta_4B film on the Si wafer and on the diamond thin film on the Si wafer is carried out. The method of carrying out this film formation will be described below.

Ta_4B is formed to a thickness of 0.5–1 μm either by film formation on a Si wafer from which surface contaminants (particles, organic matter, metal) have been removed, or by continuous formation of a diamond film. The structure of this embodiment is the same as FIG. **44** and will be omitted.

A compound of titanium and boron having a ratio of number of atoms of 4:1 is used as the sputtering target. Sputtering is carried out in an Ar or Xe atmosphere. The chamber pressure at this time is 3–500 mTorr. A process gas flow amount up to 3SLM is possible.

The results of evaluating the Ta_4B film formed on the Si wafer and on the 2 μm diamond thin film on the Si wafer to a thickness of 1 μm are shown in Table 3. From these results the following becomes clear.

(1) Using the plasma device of the present invention, film formation with high in-plane uniformity can also be obtained for a large diameter substrate.

TABLE 3

Evaluation results for amorphous Ta_4B		
	On Si substrate	On diamond thin film
Film thickness, inside 4 inch substrate (Total stepped film thickness	000 μm ± 0.008 μm	000 μm ± 0.021 μm
Surface roughness (atomic force microscope)	1 nm	6 nm

(Embodiment 40)

This embodiment shows a case where the present device is applied to a plasma CVD device for forming a polycrystalline silicon thin film on the substrate in a plasma device using a radial line slot antenna capable of uniformly supplying a large flow amount of gas.

The structure of this device is the same as embodiment 3, and will be omitted.

Description will be given for the case where a thin film is formed on a glass substrate. The foundation substrate is not limited to a glass substrate and the material can also be amorphous such as SiN_x, or SiO_2. As uses for the polycrystalline silicon thin film, it is possible to utilize it as an active layer of a transistor, or a gate electrode etc. SiH_4, Xe was used as the source material gas, but is not limited to this combination. It is also possible to replace SiH_4 with Si_2H_4, and to replace Xe with Ar or H_2 etc.

Evaluation was carried out with the gas flow amount ratio for Xe and SiH_4 set to 100:1.

Microwave power was 1600 W, and total gas flow amount of the gas introduced into the process chamber was changed from 300 sccm to 3000 sccm. The polycrystalline silicon was formed on a 300 mm glass substrate, and the surface plasma, uniformity and polycrystalline silicon crystallite size were measured. The substrate temperature was set to 300° C. This is just one example of the processing conditions for illustrating the effects of the present invention, but these conditions are not limiting.

FIG. 72 shows the dependency of surface roughness of the film formed polycrystalline silicon thin film on total gas flow amount. Measurement was carried out using an atomic force microscope (AFM). It can be seen that if the total gas flow amount is increased, surface roughness is lowered.

FIG. 73 shows the dependency of in-plane uniformity on the glass substrate of the film formed polycrystalline silicon thin film on total gas flow amount. It will be understood that the in-plane uniformity is also improved as total gas flow is increased.

FIG. 74 shows the dependency of crystallite size of the film formed polycrystalline silicon film on total gas flow amount The crystallite size was calculated based on the scheller method using a Si peak width at half height obtained by an X-ray thin film method. It will be understood that crystallite size increases accompanying increase in total gas flow amount.

FIG. 75 shows dependency of in-film hydrogen amount of the film formed polycrystalline silicon thin film on total gas flow amount. Measurement of the in-film hydrogen amount was carried out using FT-IR, and is represented by relative values. It will be understood that accompanying increase in total gas flow amount removal of reaction by-products was promoted and in-film hydrogen amount was decreased.

FIG. 76 shows the dependency of specific resistance of a film on total gas flow amount, in the case of P dopant with PH_3 added to a process gas of Xe and SiH_4. Evaluation was carried out with the flow amount ratio of Xe:SiH_4:PH_3 fixed to 100,000:1000:1, but it is not limited to these values. It will be understood that accompanying increase in total gas flow amount the specific resistance of the film becomes smaller, and the activation rate of the dopant is increased. The above effects were also conformed in the case of dopant using addition of hydrides such as AsH_3 and B_2H_6 instead of PH_3.

As has been described above, using the present invention, by being able to uniformly expel a large flow amount, removal of reaction by-products is promoted and in-plane uniformity is improved, surface roughness is reduced, and it is possible to form a high quality polycrystalline silicon thin film having large crystallite size.

(Embodiment 41)

This embodiment shows a case where the present device is applied to a plasma CVD device for forming a Si_3N_4 thin film on the substrate in a plasma device using a radial line slot antenna capable of uniformly supplying a large flow amount of gas.

The structure of this device is the same as embodiment 32, and will be omitted.

The Si_3N_4 film can be used as a gate insulation film for a TFT etc, a LOCOS mask or as a passivation film, or the like. SiH_4, Xe and N_2 are used as the source material gas, but this combination is not limiting. It is possible to replace Si_2H_4 with SiH_6, to replace Xe with Ar and to replace N_2 with NH_3. The ratio of SiH_4:Xe:N_2 is set to 1:100:5. Microwave power was 1600 W, while pressure inside the process chamber was 300 mTorr, a total gas flow amount was changed from 300 sccm to 3000 sccm. A SiN_x thin film was formed on a 300 mm glass substrate, and the uniformity and withstand voltage of the film were measured. Substrate temperature was set to 300° C.

This is just one example of the processing conditions for illustrating the effects of the present invention, but these conditions are not limiting.

FIG. 77 shows the dependency of in-plane uniformity on the glass substrate of the film formed Si_3N_4 thin film on total gas flow amount. It will be understood that accompanying increase in total gas flow amount, the in-plane uniformity is also improved.

FIG. 78 shows dependence of withstand voltage of the film formed Si_3N_4 film on the total gas flow amount. Withstand voltage was measured by making a dedicated TEG. It will be understood that withstand voltage increases accompanying increase in total gas flow amount.

FIG. 79 shows dependence of atomic level compositional ratio of Si to N in the film formed Si_3N_4 film on the total gas flow amount. Measurement was carried out using X-ray photoelectron spectroscopy. It will be understood that accompanying increase in total gas flow amount, removal of reaction by-products was promoted and the atomic level composition of the Si_3N_4 approached an ideal compositional ratio for Si and N of 3:4.

As has been described above, using the present invention, by being able to uniformly expel a large flow amount, removal of reaction by-products is promoted and in-plane uniformity is improved, and it is possible to form a high quality SiN_x thin film having high withstand voltage.

(Embodiment 42)

This embodiment shows a case where the present device is applied to a plasma CVD device for forming a dielectric thin film having low fluorocarbon type gas on the substrate in a plasma device using a radial line slot antenna capable of uniformly supplying a large flow amount of gas.

The structure of this device is the same as embodiment 32, and will be omitted.

Description will be given for the case where a dielectric thin film having low fluorocarbon type gas is formed as an interlayer insulation film between wiring layer of a semiconductor element.

A wafer on which first layer AlCu wiring is to be patterned is introduced into a cluster tool. In this process, all processing up to formation of a second layer AlCu film is carried out by a cluster tool. This cluster tool is the same as embodiment 6 and will be omitted.

After loading, surface processing of the first layer wiring surface is carried out using a mixed gas of Ne/F2. Ne/F2 is introduced into this microwave device, plasma is generated inside the chamber, the wafer surface is bleached with plasma for about 5 minutes and fluoriding processing is carried out. A dielectric thin film having low fluorocarbon type gas is then formed on the wafer in the same chamber without a break in the processing. C_4F_8, H_2, and Ar were used as the source material gas, but this combination is not limiting. It is possible to replace C_4F_8 with CF_4, to replace H_2 with O_2, and to replace Xe with Ar. The gas flow amount ration for C_4F_8, H_2, and Ar was set to 1:1:5. The microwave power was set to 1600 W, the pressure inside the process chamber was set to 10–200 mTorr, and the total gas flow amount was changed from 500 sccm to 3000 sccm. Film formation was carried out on the wafer and the deposition rate and uniformity (of the deposition rate) were measured. The wafer temperature was controlled to 250 degrees.

It goes without saying that the film formation conditions are not limited to those described above.

FIG. 80 shows the dependency of the deposition rate of the film formed fluorocarbon film on total gas flow amount. It will be understood that if the total gas flow amount is caused to increase, the removal of reaction by-products is promoted, and deposition rate is increased, reaching 800 nm/min or more.

Also, FIG. 81 shows the dependency of in-plane uniformity of the deposition rate on the total gas flow rate. It will be understood that by sufficiently increasing the process gas flow amount improvement can be seen in the wafer in-plane uniformity.

As has been described above, by using the plasma device of the present invention, high speed and uniform film

formation is possible on a large surface area. Also, if film formation for two wiring layers is carried continuously in the cluster tool without a break in the process, it is possible to manufacture a semiconductor having multiple layer wiring.

(Embodiment 43)

This embodiment shows a case where the present device is applied to a plasma CVD device for forming a BST thin film [(Ba, Sr) TiO_3 thin film] on the substrate in a plasma device using a radial line slot antenna capable of uniformly supplying a large flow amount of gas.

The structure of this device is the same as embodiment 32, and will be omitted. This process uses a BST film as an insulating film of a capacitor within a semiconductor element, and within processes from formation of a lower electrode of the capacitor up to formation of an upper electrode, it carries out all processes except for lithography processing and wafer cleansing process inside a cluster tool. The features of this cluster tool are the same as embodiment 6 and will be omitted. First of all, the substrate is loaded into the cluster tool and a poly-Si lower electrode is formed. An Ru/RuO_x film is also formed. A BST film is formed without a break in the process.

In this example, $Ba(DPM)_2$, $Sr(DPM)_2$, $Ti(I\text{-}OC_3H_7)_4$ O_2 and Ar are used as the source material gas, but this combination is not limiting and it possible to replace Ar with Xe. Process gas comprising $Ba(DPM)_2$, $Sr(DPM)_2$, $Ti(I\text{-}OC_3H_7)_4$ is introduced into the device from the gas inlet with Ar as a carrier gas. Also, Ar and O_2 are introduced into the process chamber at a ratio of 1:2, as additional gas. Microwave power was set to 1600 W and pressure inside the process chamber was set to 10–200 mTorr, and additional gas flow amount was changed from 500 sccm to 3000 sccm. At this time, only the flow amount of the additional gas was caused to change, and processing was carried out without changing the supply condition for the $Ba(DPM)_2$, $Sr(DPM)_2$, $Ti(I\text{-}OC_3H_7)_4$. Film formation was carried out on a 300 mm wafer, and deposition rate and uniformity of the deposition rate were measured. It goes without saying that the film formation conditions are not limited to these described above.

FIG. **82** shows the dependency of deposition rate of the BST film on additional gas flow amount. If additional gas flow is increased there is a tendency for the deposition rate to decrease. Also, FIG. **83** shows the dependency of in-plane uniformity of the deposition rate on the additional gas flow rate. It will be understood that by sufficiently increasing the process gas flow amount improvement can be seen in the wafer in-plane uniformity, and in-plane uniformity of less than ±2% is achieved with a 300 mm substrate.

As has been described above, by using the plasma device of the present invention formation of a uniform and high quality film is possible on a large surface area. Also, if film formation of TiN as an upper electrode is carried out after BST film formation, it is possible to manufacture a capacitor for use in semiconductor element.

In this embodiment, poly-Si, TiN and Ru/RuO_x have respectively been used as lower and upper electrodes of a capacitor and a stacked electrode, but it goes without saying that the present invention can also be applied in the case where Pt, Ta, W, Mo, Rh, In, InO_x, $TiSi_x$ etc. are used. In this embodiment, a BST film has been used as a capacitor insulation film, but it goes without saying that the same effects as in this embodiment are also obtained in the case where PZT or $SrTiO_3$ etc. are used.

(Embodiment 44)

FIG. **84** is a cross section of a device manufactured using the present invention.

All the following processes, except for wafer cleansing and lithography processes were carried out using a cluster tool.

Part of the cluster tool is shown in FIG. **85**. The characteristic of this cluster tool is that by connecting between each process chamber using an Ar or N_2 tunnel, thin film formation can be carried out continuously under an extremely pure atmosphere without exposing the semiconductor, metal, or insulator on the substrate to the atmosphere at all. Also, each process chamber achieves an ultra high vacuum state of the ultimate vacuum of 10^{-10} Torr, but at the time of conveying the wafer, a number of mTorr to several tens of Torr is maintained using very pure Ar or N_2 and contamination of the wafer surface by organic matter or moisture etc. is prevented. Further, conveyance between each cluster is carried out using a port sealed encapsulated with N_2 or dry air, and wafer cleansing and lithographic processing is also carried out in an N_2 or dry air atmosphere, and it is possible to carry out processing that completely excludes all sorts of impurity elements from the atmosphere.

An SOI wafer from which an oxidation film in the vicinity of the surface has been removed is loaded into the cluster tool **6101**. After loading, a Ta thin film is formed to a thickness of 1–50 nm with a plasma processing device using a uniform horizontal magnetic field of the present invention shown in FIG. **54**. At this time, by controlling a high frequency applied to the entire surface of the wafer, ion irradiation energy is controlled and it is possible to obtain Ta of desirable film quality. Next, the wafer was introduced into the plasma processing device using the radial line slot antenna of the present invention shown in FIG. **53**, plasma oxidation was carried out in a $Ar/He/O_2$, Xe/O_2 or $Xe/He/O_2$ atmosphere, only the Ta film formed in the previous process was oxidized and a tantalum oxide thin film **6001** was obtained. The pressure at the time of plasma oxidation was 3–500 mTorr and the wafer was temperature controlled to 300–500° C. A Ta thin film **6002** constituting a gate electrode was also formed to a thickness of 0–1–2 μm with the plasma processing device using the uniform horizontal magnetic field of the present invention shown in FIG. **54**. Consecutively, a CVD NSG film was formed to a thickness of 1–50 nm using the plasma processing device using the radial line slot antenna of the present invention shown in FIG. **53**. With this cap processing, it is possible to selectively form tantalum oxide only on the gate side surface, and it is easy to carry out etching processing at the time of forming contact holes on the gate electrode with a high selectivity.

Next, using the plasma processing device using the uniform horizontal magnetic field of the present invention shown in FIG. **44**, gate etching is carried out. The process for forming the barrier metal in this step is shown in detail in FIG. **85**. By using this device, in-plane uniformity is high even for a large diameter substrate, and fine processing is possible. High purity ion injection is carried out in a self aligned manner, and after activation annealing for 450–550° C. a source drain region **6003** was formed (a). Oxidation was carried out similarly to previously, as side wall **6004** processing, using the plasma processing device using the radial line slot antenna of the present invention shown in FIG. **53**(*b*).

After SiO_2 of the Si surface has been removed by wet etching, a Ta film is formed to 2–100 nm (c). Ta and S/D section Si of the surface are made amorphous and mixed by I/I, and after that tantalum silicide **6006** is formed by annealing (d). After that, patterning is performed (e) and after Ta has been etched using the plasma processing device using the uniform horizontal magnetic field of the present

invention shown in FIG. **44**(*f*), a cap SiO_2 is removed by wet etching (g). After that, barrier metal formation **6006** is carried out (h). Next, the wafer was introduced into the plasma processing device using the radial line slot antenna of the present invention shown in FIG. **53**, and plasma nitridation was carried out in an N2, Ar/N_2, or Xe/N_2 atmosphere. Film thickness was 10–500 nm. The pressure at the time of plasma oxidation was 3–500 mTorr and the wafer was temperature controlled to 300–550° C.

Also, a CVD NSG film **6007** is formed using the plasma processing device using the radial line slot antenna of the present invention shown in FIG. **53**, flattened by CMP, and contact etching is carried out using the plasma processing device using the uniform horizontal magnetic field of the present invention shown in FIG. **44**.

Capacitor formation is carried out by oxidizing a surface layer to 5–500 nm after film formation of the lower Ta electrode **6008** to a thickness of 0.1–2 μm, forming tantalum oxide **6009**, and film forming the upper Ta electrode **6010** to 0.1–2 μm. These processes are also carried out with the plasma processing device using the radial slot line antenna and the plasma processing device using the uniform horizontal magnetic field of the present invention.

After formation of these elements, formation of Cu wiring **6011** is carried out and the device is completed. In the case where Ta nitride is used as barrier metal between the wiring, a process for forming barrier metal on the gate electrode is applied accordingly.

A tantalum oxide gate insulation FET or tantalum oxide capacitor formed in this way was electrically evaluated.

FIG. **86** shows distribution of a subthreshold coefficient of a tantalum oxide gate insulation MOSFET. A device having only the gate insulation film formation using the plasma device of the related art has a largely distributed subthreshold coefficient, but in the present invention high uniformity is realized.

The initial failure rate of MOSFETs in the case of carrying out a process of forming titanium nitride formation, as barrier metal, using the plasma device of the present invention, and the initial failure rate of examples that used the present invention, as well as samples after carrying out heating tests for 24 hours at 700° C. in the atmosphere, are shown in FIG. **87**. With the technique of the related art, initial failure rate at the wafer edge is low, but Cu used as wiring material in this case diffuses into imperfect tantalum nitride. In the present invention, the entire surface of the wafer exhibits a low failure rate.

FIG. **88** shows in-plane uniformity of the capacitance of a tantalum oxide capacitor. In the related art, there is a tendency for film thickness to increase in the radial direction, but with the present invention it is possible to obtain a uniform capacitance over the entire surface.

In this embodiment, an SOI wafer is used as the starting wafer, but it goes without saying that it is also possible to obtain the same results in this embodiment if a Si wafer, Si epitaxial wafer, metal substrate SOI wafer, GaAs wafer or diamond wafer, or a substrate having a thin film of Si, epitaxial Si, GaAs or diamond formed on the surface of quartz, glass, ceramics or plastic etc. are used.

Ta is used as a MOSFET gate electrode in this embodiment, but it goes without saying that the same effects can be obtained if n^+ polysilicon or p^+ polysilicon is used. In this embodiment a mixed gas of a carrier gas of Ar, Xe, He, etc. and O_2 is used as oxidation process gas, but it goes without saying that the same effects can be obtained with this embodiment if a mixed gas of another carrier gas and an oxide (for example H_2O, NO_x etc.) is used as the mixed gas.

In this embodiment, a mixed gas of a carrier gas of Ar, Xe, etc. and N_2 is used as the nitridation process gas, but it goes without saying that the same effects can be obtained with this embodiment if a mixed gas of another carrier gas and a nitride(for example NH_3 etc.) is used as the mixed gas.

Ta is used in this embodiment in the upper and lower electrodes, but it goes without saying that the same effects can be obtained with this embodiment if Pt, Ru, Ti, W, Mo, RuO_x, TiN_x, WN_x, $TaSi_xN_y$, $TiSi_xN_y$, Wsi_xN_y etc., or a stacked electrode comprising these materials is used.

In this embodiment only tantalum oxide has been dealt with as a MOSFET gate insulation film and capacitor insulation film, but it goes without saying that the same effects can be obtained with this embodiment if a stacked insulation film of tantalum oxide and SiO_2 or Si_3N_4, BST and PZT is used.

SiO_2 is used in this embodiment as a cap material for MOSFET gate processing, but it goes without saying that the same effects can be obtained with this embodiment if a material such as Si, or Si_3N_4 is used.

In this embodiment Ta oxidation is carried out as a MOSFET gate side wall process, but it goes without saying that the same effects can be obtained with this embodiment if a sidewall is formed by using this process as a re-oxidation process and using a new NSG etc.

In this embodiment formation of TaN_x, being barrier metal, is carried out using Ta, but it goes without saying that the same effects can be obtained as in this embodiment if $TaSi_xN_y$ is formed using $TaSi_x$.

TaN_x is used in this embodiment as a barrier metal but it goes without saying that the same effects can be obtained with this embodiment if a material such as TiN_x, WN_x $TaSi_xN_y$, $TiSi_xN_y$ or Wsi_xN_y is used.

In this embodiment, a mixed logic type device has been manufactured, but it goes without saying that the same effects can be obtained with this embodiment if a logic LSI or DRAM etc. are used independently of each other.

(Embodiment 45)

FIG. **89** shows the expel characteristics of a turbo molecular pump expulsion characteristics of pumps respectively having exhaust rates of 220, 540 and 1800 l/sec at a low pressure region, and expel characteristics in the case of expel with four pumps having an exhaust rate of 220 l/sec are shown. When the exhaust rate is not fixed by pressure, pump inlet pressure and expel gas flow amount are proportional. From the drawing it will be understood that in a high pressure region exhaust rate is decreased accompanying increased pressure. It will also be understood that compared to a pump having a small exhaust rate, a pump having a large exhaust rate has a further decrease in exhaust rate from a low pressure region. In a pump having a small exhaust rate of 220 l/sec, substantially no decrease in exhaust rate was observed at a low pressure region of 20–30 Torr for carrying out etching processing. That is, a plurality of small diameter pumps having small exhaust rate are advantageous in that they can cause a larger flow amount of gas at a low pressure region for carrying out normal semiconductor processing than a single large diameter pump having a high exhaust rate.

(Embodiment 46)

FIG. **90**–FIG. **92** are plan views showing examples of the plasma device of the present invention used as cluster tools for carrying out continuous processing by conveying between vacuums.

FIG. **90** is a case where rectangular process chambers and a rectangular wafer conveyance chamber are joined together. Reference numeral **9001** is a wafer take in chamber, refer-

ence numeral **9002** is a wafer take out chamber, reference numeral **9003** is a process chamber **1**, reference numeral **9004** is a process chamber **2**, reference numeral **9005** is a wafer conveyance chamber, and reference numeral **9006** is a gate valve. The process chambers 1 and 2 are any of the chambers disclosed in FIG. **44**, or FIG. **48**–FIG. **54**. For example, process chamber **1** is an etching chamber and process chamber **2** is a resist ashing chamber. One or a plurality of wafer conveyance ports are provided inside the wafer conveyance chamber **9005**, and wafer delivery is carried out for the process chamber and the wafer take in/take out chambers.

In the example of FIG. **90**, miniature process chambers are efficiently arranged, and the area that the cluster tool occupies in the clean room is extremely small. It is possible to make the footprint of a cluster tool for a wafer having a diameter of 300 mm even smaller than the smallest footprint of a cluster tool for a wafer of 300 mm in the related art. With the structure of FIG. **90**, the footprint of a cluster tool for a 300 mm diameter wafer is 3.64 mm^2, which is about 0.9 times the footprint of the smallest cluster tool for a 200 mm diameter wafer in the related art. The number of chambers connected to the conveyance chamber is not limited to six.

FIG. **91** is for a case where rectangular process chambers and a hexagonal wafer conveyance chamber are joined together. Reference numeral **9101** is a wafer take in chamber, reference numeral **9102** is a wafer take-out chamber, reference numeral **9103** is process chamber **1**, reference numeral **9104** is process chamber **2**, and reference numeral **9105** is a wafer conveyance chamber. The process chambers **1** and **2** are any of the process chambers disclosed in FIG. **44** or FIG. **46**–FIG. **54**. For example, process chamber **1** is an etching chamber and process chamber **2** is a resist ashing chamber.

Since it is permissible to only locate a single wafer conveyance port inside the wafer conveyance chamber, the cost is reduced compared to the case in FIG. **90**. On the other hand, the footprint of the device becomes slightly larger than the case in FIG. **90**. With the structure of FIG. **91**, the footprint of a cluster tool for a **300**mm diameter wafer becomes 4.34 mm^2. This is about the same as the footprint of the smallest cluster tool for a 200 mm diameter wafer in the related art. The wafer conveyance chamber is not limited in shape to a hexagon, and the number of chambers connected to the wafer conveyance chamber is not limited to six.

FIG. **92** is for a case where triangular process chambers and a hexagonal wafer conveyance chamber are joined together. Reference numeral **9201** is a wafer take in chamber, reference numeral **9202** is a wafer take-out chamber, reference numeral **9203** is process chamber **1**, reference numeral **9204** is process chamber **2**, and reference numeral **9205** is a wafer conveyance chamber. The process chambers **1** and **2** are any of the process chambers disclosed in FIG. **44** or FIG. **48**–FIG. **54**. For example, process chamber **1** is an etching chamber and process chamber **2** is a resist ashing chamber.

Since the number of vacuum pumps is low, the cost is reduced compared to the cases of FIG. **90** and FIG. **91**, and it is possible to widen a maintenance space of the device. On the other hand, the footprint of the device is slightly larger than in the case of FIG. **91**. With the structure of FIG. **92**, the footprint of a cluster tool for a 300 mm diameter wafer becomes 4.94 mm^2. The wafer conveyance chamber is not limited in shape to a hexagon, and the number of chambers connected to the wafer conveyance chamber is not limited to six. FIG. **90**–FIG. **92** are cases where two types of process chamber are joined together two at a time, but other combinations are also possible.

FIG. **93**–FIG. **95** show arrangements of wafer conveyance robots inside the wafer conveyance chamber of FIG. **90**. In FIG. **93**, reference numeral **9301** is a wafer take-in chamber, reference numeral **9302** is a wafer take-out chamber, reference numeral **9303** is a process chamber, reference numeral **6304** is a wafer conveyance chamber, reference numeral **9305** is a wafer conveyance robot, and reference numeral **9306** is a wafer withdrawal unit. The wafer conveyance robot **9305***a* carries out wafer delivery between the wafer take-in chamber **9301**, the wafer take-out chamber **9302** and the wafer withdrawal unit **9306***a*. The wafer conveyance robot **9305***b* carries out wafer delivery between the process chambers **9303***a* and **9303***c*, and the wafer withdrawal units **9303***a* and *b*. The wafer withdrawal unit **9306** has a function of holding one or a plurality of wafers. The wafer withdrawal unit can also serve to align ?? and notch positions of the wafer, or to heat and cool the wafer.

In the example of FIG. **93**, wafer delivery between wafer conveyance robots is carried out via the wafer withdrawal units, but the wafers can be delivered directly without installing the wafer withdrawal units. In the example of FIG. **93**, since a plurality of wafer conveyance robots are provided, wafers can be taken into and taken out of the wafer take-in/take-out chambers and each of the processes chambers at the same time. As a result, the time needed to convey the wafers is shortened and throughput is increased.

FIG. **94** is a structure comprising a plurality of the wafer conveyance chambers of FIG. **93**. Reference numeral **9401** is a wafer conveyance chamber and reference numeral **9401** is a wafer withdrawal chamber. By varying the number of connected wafer conveyance chambers **9401** and wafer withdrawal units **9402**, it is possible to arbitrarily vary the number of connected process chambers. It is also possible to routinely minimize the footprint of the cluster tool for an arbitrary number of process chambers.

In FIG. **95**, reference numeral **9501** is a wafer conveyance robot. The wafer conveyance robot **9501** can move in the direction of the arrows in the drawing, and a single wafer conveyance robot carries out taking in and taking out of wafers for all wafer take-in/take out chambers and process chambers. In this example, since there is only need for a single wafer conveyance robot, the cost is reduced compared to the case of FIG. **93**. On the other hand, the time need to convey the wafer is lengthened and it is possible that throughput will be lowered.

Industrial Applicability.

As has been described above, according to the present invention, it is possible to realize a plasma device capable of forming a high quality and uniform thin film over a large surface area and at low temperature.

Also, the technical concept of the present invention is applicable to various plasma processes, and can realize a general purpose device, which means that it is also possible to significantly reduce maintenance costs etc.

What is claimed is:

1. A plasma device comprising:

a container, the inside of which can be internally decompressed, and part of the inside being formed of a first dielectric plate made of material capable of transmitting microwaves with almost no loss,

a gas supply system for supplying essential source material gas so as to cause excitation of plasma inside the container,

an exhaust system for expelling said source material gas that has been supplied into the container and decompressing the inside of the container,

an antenna, located facing an outer surface of the first dielectric plate and comprised of a slot plate and a waveguide dielectric, for radiating microwaves, said slot plate electrically in connection with said container and

an electrode for holding an object to be treated located inside the container, a surface of the object to be treated to be subject to plasma processing and a microwave radiating surface of the antenna being arranged in parallel substantially opposite to each other, and the plasma device carrying out plasma processing for the object to be treated, wherein,

a wall section of the container outside the first dielectric plate is of a material comprising matter having a conductivity of $3.7\times10^7\ \Omega^{-1}\cdot m^{-1}$ or more, or the inside of the wall section is covered with this material, and

where thickness of the material is d, the specific conductivity of the material is a, the magnetic permeability of vacuum is μ_0, and the angular frequency of microwaves radiated from the antenna is ω, the thickness d is larger than $(2/\mu_0\sigma\omega)^{1/2}$.

2. The plasma device as disclosed in claim 1, wherein the first dielectric plate is formed of a material having a dielectric loss angle tan δ in said microwave frequency of less than 5×10^{-3}.

3. The plasma device as disclosed in claim 1, wherein a space is formed between the antenna and the first dielectric plate.

4. The plasma device as disclosed in claim 3, wherein a line for supplying heat exchanging medium communicates with the space formed between the antenna and the first dielectric plate.

5. The plasma device as disclosed in claim 1, provided with means for cooling the antenna.

6. The plasma device as disclosed in claim 5, wherein a passageway is formed in said antenna waveguide, and a line for supplying heat exchanging medium communicates with the passageway.

7. The plasma device as disclosed in claim 1, provided with means for cooling the first dielectric plate.

8. The plasma device as disclosed in claim 1, provided with means for preventing warping of the slot plate.

9. The plasma device as disclosed in claim 8, wherein a space is provided between the antenna and the first dielectric plate, and a plate composed of a flexible member is interposed in the space as means for preventing warping of the slot plate.

10. The plasma device as disclosed in claim 1, provided with means for detecting the presence or absence of plasma generated in the space device.

11. The plasma device as disclosed in claim 1, provided with a mechanism for causing the temperature of a wall section inside the container and sections inside the container other than the object to be treated, to respectively rise to 150° C.

12. The plasma device as disclosed in claim 1, wherein the exhaust system is provided with a mechanism for causing the temperature inside all units comprising the exhaust system, to respectively to rise to 150° C.

13. The plasma device as disclosed in claim 1, wherein the electrode having the function of holding the object to be treated has a mechanism for heating the object to be treated.

14. The plasma device as disclosed in claim 13, wherein a xenon lamp is used as the mechanism for heating the object to be treated.

15. The plasma device as disclosed in claim 1, wherein a mechanism for collecting and recycling fluorocarbon type gas is provided downstream of the exhaust system.

16. The plasma device as disclosed in claim 1, wherein a film comprising AlF_3 and MgF_2 is formed on an inner wall surface of the container.

17. The plasma device as disclosed in claim 1, wherein the electrode having the function of holding the object to be treated is provided with at lease one of a dc bias and ac bias applying means.

18. The plasma device as disclosed in claim 1, wherein said plasma device is a device for carrying out etching of a surface the object to be treated.

19. The plasma device as disclosed in claim 1, wherein said plasma device is a device for causing direct oxidation of a surface of the object to be treated.

20. The plasma device as disclosed in claim 1, wherein said plasma device is a device for causing direct nitridation of a surface of the object to be treated.

21. The plasma device as disclosed in claim 1, wherein said plasma device is a device for causing a thin film to be deposited on the object to be treated.

22. A plasma device comprising:

a container, the inside of which can be internally decompressed, and part of the inside being formed of a first dielectric plate made of material capable of transmitting microwaves with almost no loss,

a gas supply system for supplying essential source material gas so as to cause excitation of plasma inside the container,

an exhaust system for expelling said source material gas that has been supplied into the container and decompressing the inside of the container,

an antenna, located facing an outer surface of the first dielectric plate and comprised of a slot plate and a waveguide dielectric, for radiating microwaves, and

an electrode for holding an object to be treated located inside the container, a surface of the object to be treated to be subject to plasma processing and a microwave radiating surface of the antenna being arranged in parallel substantially opposite to each other, and the plasma device carrying out plasma processing for the object to be treated, wherein,

a wall section of the container outside the first dielectric plate is of a material comprising matter having a conductivity of $3.7\times10^7\ \Omega^{-1}\cdot m^{-1}$ or more, or the inside of the wall section is covered with this material,

where thickness of the material is d, the specific conductivity of the material is σ, the magnetic permeability of vacuum is μ_0, and the angular frequency of microwaves radiated from the antenna is ω, the thickness d is larger than $(2/\mu_0\sigma\omega)^{1/2}$,

a first O ring is located between an inner surface of the first dielectric body and a wall section of the container; and

a thin film formed of a conductive material is provided on at least a surface of the first dielectric plate coming into contact with the first O ring, as means for preventing the first O ring from being directly exposed to microwaves radiated from the antenna.

23. The plasma device as disclosed in claim 22, wherein said thin film is formed from a material having a conductivity of at least $3.7\times10^7\ \Omega^{-1}\cdot m^{-1}$, and has a thickness of at least 10 μm.

24. A plasma device comprising:

a container, the inside of which can be internally decompressed, and part of the inside being formed of a first dielectric plate made of material capable of transmitting microwaves with almost no loss,

a gas supply system for supplying essential source material gas so as to cause excitation of plasma inside the container,

an exhaust system for expelling said source material gas that has been supplied into the container and decompressing the inside of the container,

an antenna, located facing an outer surface of the first dielectric plate and comprised of a slot plate and a waveguide dielectric, for radiating microwaves,

an electrode for holding an object to be treated located inside the container, a surface of the object to be treated to be subject to plasma processing and a microwave radiating surface of the antenna being arranged in parallel substantially opposite to each other, and the plasma device carrying out plasma processing for the object to be treated, wherein,

a wall section of the container outside the first dielectric plate is of a material comprising matter having a conductivity of $3.7\times10^7\ \Omega^{-1}\bullet m^{-1}$ or more, or the inside of the wall section is covered with this material,

where thickness of the material is d, the specific conductivity of the material is σ, the magnetic permeability of vacuum is μ_0, and the angular frequency of microwaves radiated from the antenna is ω, the thickness d is larger than $(2/\mu_0\sigma\omega)^{1/2}$,

a first O ring having a vacuum sealing function is located between an inner surface of the first dielectric body and a wall section of the container; and

a thin film formed of a conductive material is coated on the surface of the first O ring, for preventing the first O ring from being directly exposed to microwaves radiated from the antenna.

25. The plasma device as disclosed in claim **24**, wherein said metallic thin film is formed from a material having a conductivity at least $3.7\times10^7\ \Omega^{-1}\bullet m^{-1}$, and has a thickness of at least 10 μm.

26. A plasma device comprising:

a container, the inside of which can be internally decompressed, and part of the inside being formed of a first dielectric plate made of material capable of transmitting microwaves with almost no loss,

a gas supply system for supplying essential source material gas so as to cause excitation of plasma inside the container,

an exhaust system for expelling said source material gas that has been supplied into the container and decompressing the inside of the container,

an antenna, located facing an outer surface of the first dielectric plate and comprised of a slot plate and a waveguide dielectric, for radiating microwaves, said slot plate electrically in connection with said container and

an electrode for holding an object to be treated located inside the container, a surface of the object to be treated to be subject to plasma processing and a microwave radiating surface of the antenna being arranged in parallel substantially opposite to each other, and the plasma device carrying out plasma processing for the object to be treated;

where thickness of the material is d, the specific conductivity of the material is σ which is more than $3.7\times10^7\ \Omega^{-1}\bullet m^{-1}$, the magnetic permeability of vacuum is μ_0, and the angular frequency of microwaves radiated from the antenna is ω, the thickness d is larger than $(2/\mu_0\sigma\omega)^{1/2}$,

wherein a second dielectric plate having a gas inlet for substantially uniformly supplying desired gas is provided between the first dielectric plate and the electrode for holding the object to be processed.

27. The plasma device as disclosed in claim **26**, wherein:

a second O ring having a vacuum sealing function is located between an inner surface of the second dielectric body and a wall section of the container; and

a thin film formed of a conductive material is provided on at least a surface of the second dielectric plate coming into contact with the second O ring, as means for preventing the second O ring from being directly exposed to microwaves radiated from the antenna.

28. The plasma device as disclosed in claim **26**, wherein:

a second O ring having a vacuum sealing function is located between an inner surface of the second dielectric body and a wall section of the container; and

a thin film formed of a conductive material is coated on the surface of the second O ring, as means for preventing the second O ring from being directly exposed to microwaves radiated from the antenna.

29. The plasma device as disclosed in claim **26**, wherein the second dielectric plate is formed of material having a dielectric loss angle tan δ in said microwave frequency of less than 5×10^{-3}.

30. The plasma device as disclosed in claim **6**, provided with means for generating a pressure difference so that a first pressure of the first space between the first dielectric plate and the second dielectric plate is 1000 Pa or higher than a second pressure of the second space, in which the electrode for holding the object to be treated is located, and which is surrounded by the second dielectric plate and a wall section of the container other than the second dielectric plate.

31. The plasma device of claim **30**, the antenna being provided with a slot plate functioning as a microwave radiating surface, and slot sets comprising holes penetrating the slot plate at a plurality of fixed locations wherein, at portions where the density of plasma generated in the space is locally higher than other portions, the slots either have a smaller diameter than at other portions, are screened by a screen plate, or are not provided at all.

32. The plasma device as disclosed in claim **26**, wherein means for introducing heat exchanging medium is connected into the space surrounded by the second dielectric plate and a wall section of the container other than the second dielectric plate.

33. A plasma device comprising:

a container, the inside of which can be internally decompressed, and part of the inside being formed of a first dielectric plate made of material capable of transmitting microwaves with almost no loss,

a gas supply system for supplying essential source material gas so as to cause excitation of plasma inside the container,

an exhaust system for expelling said source material gas that has been supplied into the container and decompressing the inside of the container,

an antenna, located facing an outer surface of the first dielectric plate and comprised of a slot plate and a waveguide dielectric, for radiating microwaves, and

an electrode for holding an object to be treated located inside the container, a surface of the object to be treated to be subject to plasma processing and a microwave radiating surface of the antenna being arranged in parallel substantially opposite to each other, and the plasma device carrying out plasma processing for the object to be treated, wherein,

a wall section of the container outside the first dielectric plate is of a material comprising matter having a conductivity of $3.7\times10^{7}\ \Omega^{-1}\cdot m^{-1}$ or more, or the inside of the wall section is covered with this material, and

where thickness of the material is d, the specific conductivity of the material is σ, the magnetic permeability of vacuum is μ_0, and the angular frequency of microwaves radiated from the antenna is ω, the thickness d is larger than $(2/\mu_0\sigma\omega)^{1/2}$,

wherein a second dielectric plate having a gas inlet for substantially uniformly supplying desired gas is provided between the first dielectric plate and the electrode for holding the object to be processed,

and a width of a first space between the first dielectric plate and the second dielectric plate is less than 1.0 mm and uneven thereby forming a gas passage.

* * * * *

US006172321B1

(12) United States Patent
Yoshioka et al.

(10) **Patent No.: US 6,172,321 B1**
(45) **Date of Patent: Jan. 9, 2001**

(54) **METHOD AND APPARATUS FOR PLASMA PROCESSING APPARATUS**

(75) Inventors: **Ken Yoshioka**; **Saburou Kanai**, both of Hikari; **Tetsunori Kaji**, Tokuyama; **Ryoji Nishio**, Kudamatsu; **Manabu Edamura**, Niihari-gun, all of (JP)

(73) Assignee: **Hitachi, Ltd.**, Tokyo (JP)

(*) Notice: Under 35 U.S.C. 154(b), the term of this patent shall be extended for 0 days.

(21) Appl. No.: **09/433,551**

(22) Filed: **Nov. 4, 1999**

Related U.S. Application Data

(62) Division of application No. 08/649,190, filed on May 17, 1996, now Pat. No. 6,034,346.

(30) **Foreign Application Priority Data**

May 19, 1995 (JP) 7-120992
Aug. 8, 1995 (JP) 7-202016

(51) **Int. Cl.**^{7} **B23K 10/00**
(52) **U.S. Cl.** .... **219/121.41**; 219/121.43; 156/345; 118/723 MR; 204/298.38
(58) **Field of Search** .... 219/121.4, 121.43, 219/121.41; 204/298.37, 238.38, 298.21; 315/111.51; 156/345, 643.1, 643.3; 118/723 I, 723 MR

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,906,900	3/1990	Asmussen .
5,003,152	3/1991	Matsuo et al. .
5,024,716	6/1991	Sato .
5,034,086	7/1991	Sato .
5,134,965	8/1992	Tokuda .
5,202,095	4/1993	Houchin et al. .
5,245,157	9/1993	Ohiwa .
5,280,154	1/1994	Cuomo et al. .
5,321,222	6/1994	Bible et al. .
5,478,459	12/1995	Latz .
5,480,533	1/1996	Yoshida .
5,717,294	2/1998	Sakai et al. .

FOREIGN PATENT DOCUMENTS

41 18 973 A1	12/1992	(DE) .
43 37 119 A1	5/1995	(DE) .
0 357 824 A1	3/1990	(EP) .
0 468 886 A2	1/1992	(EP) .
0 607 797 A1	7/1994	(EP) .
4-358077	12/1992	(JP) .
6-112161	4/1994	(JP) .
7-022397	1/1995	(JP) .

Primary Examiner—Mark Paschall
(74) *Attorney, Agent, or Firm*—Antonelli, Terry, Stout & Kraus, LLP.

(57) **ABSTRACT**

A plasma processing apparatus and method of processing a specimen by a plasma. The method and apparatus includes independently controlling a density distribution of the plasma.

4 Claims, 11 Drawing Sheets

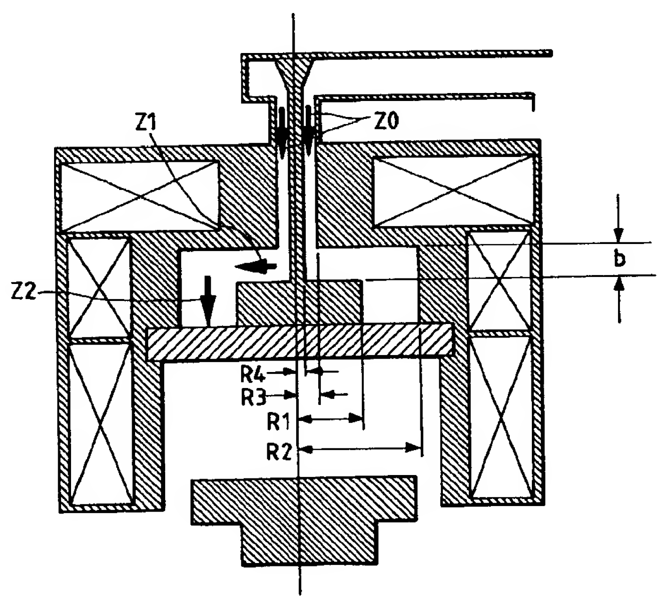


FIG. 1

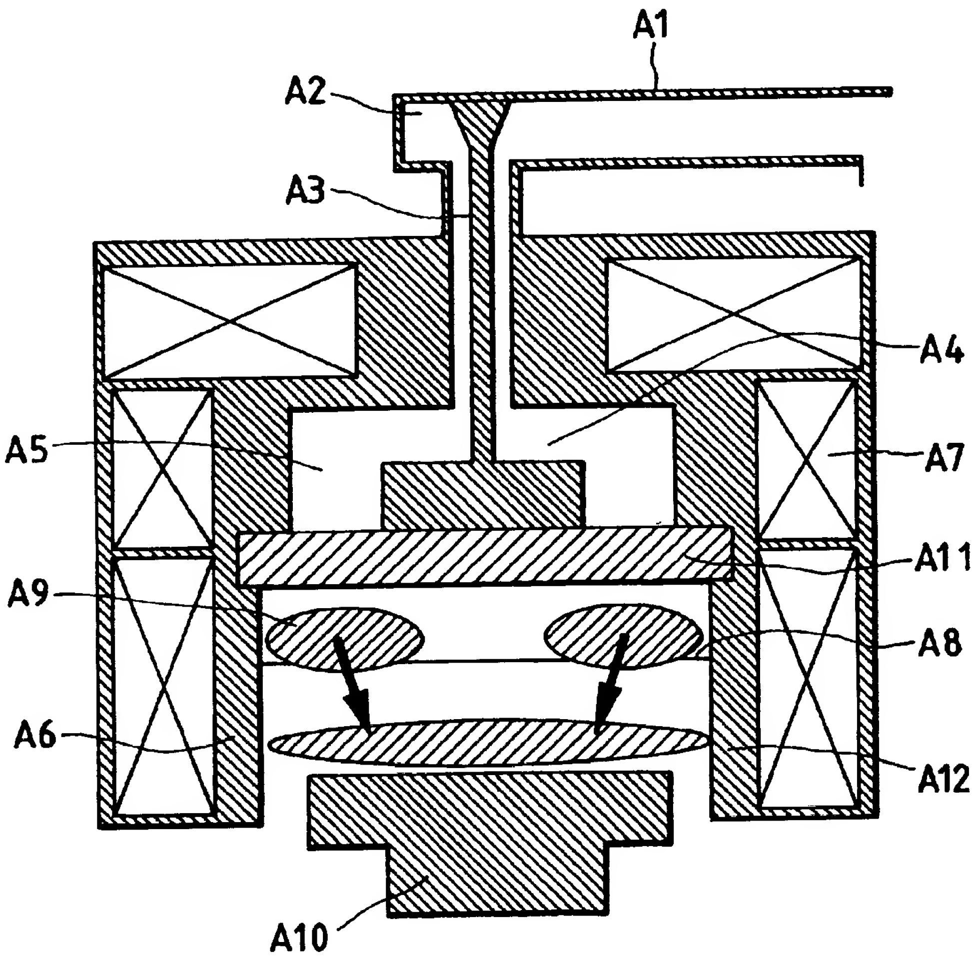


FIG. 2(a)

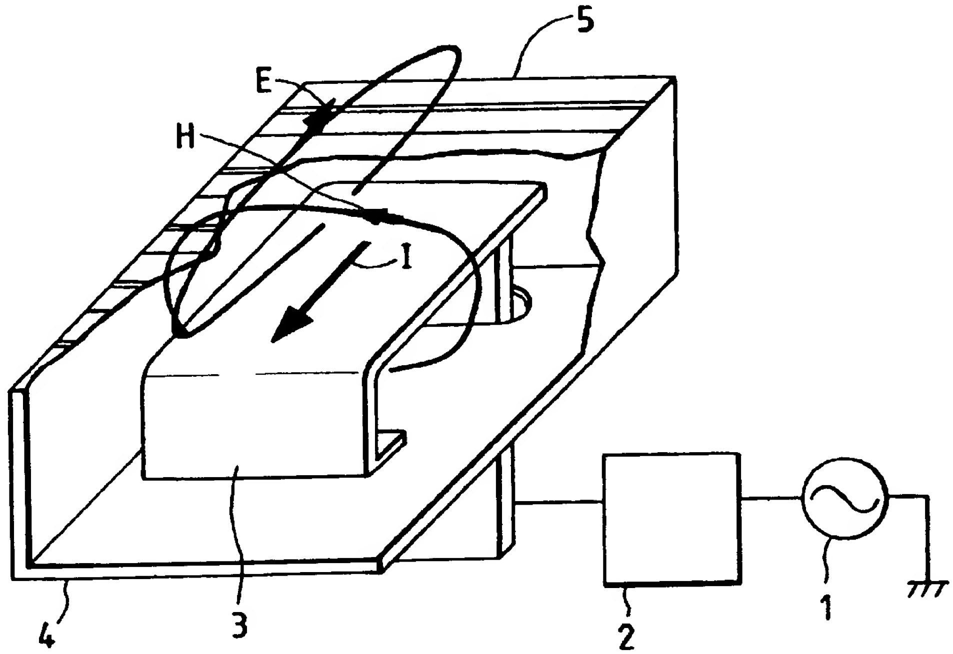


FIG. 2(b)

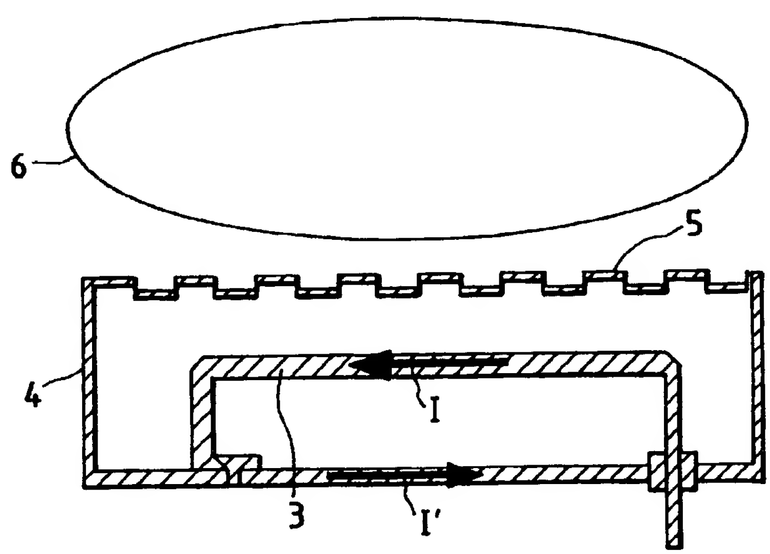


FIG. 3(a)

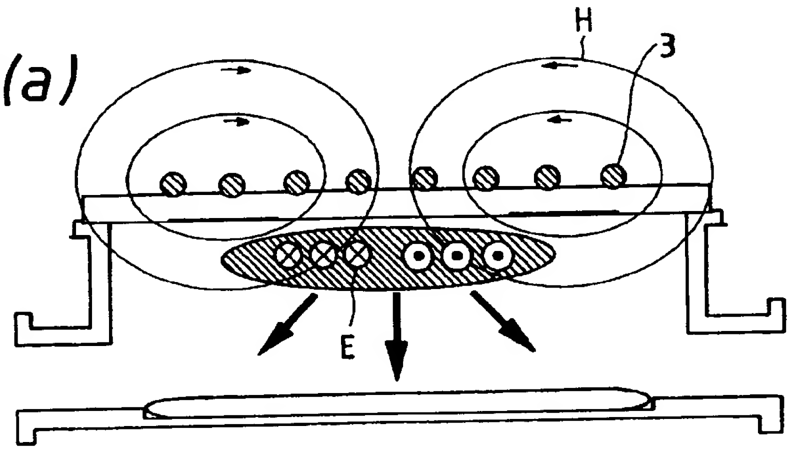


FIG. 3(b)

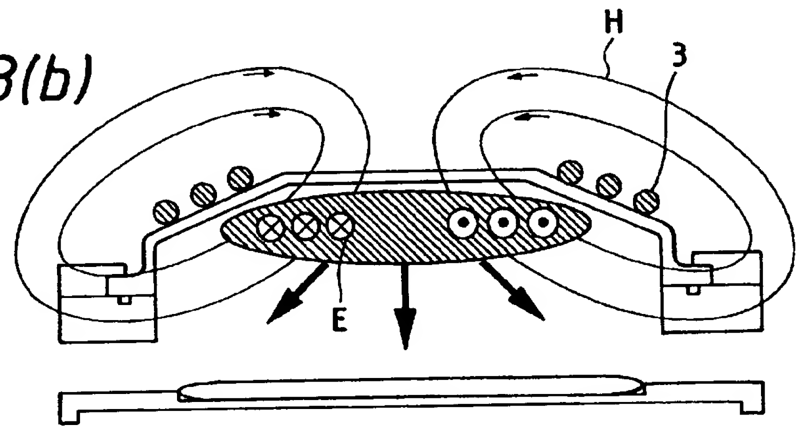


FIG. 3(c)

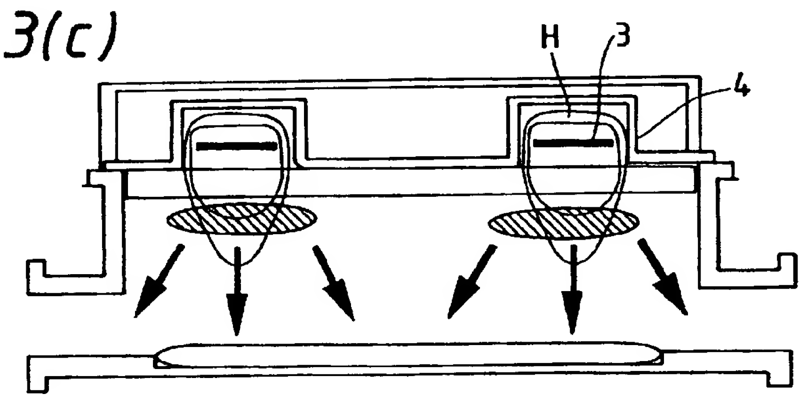


FIG. 4(a)

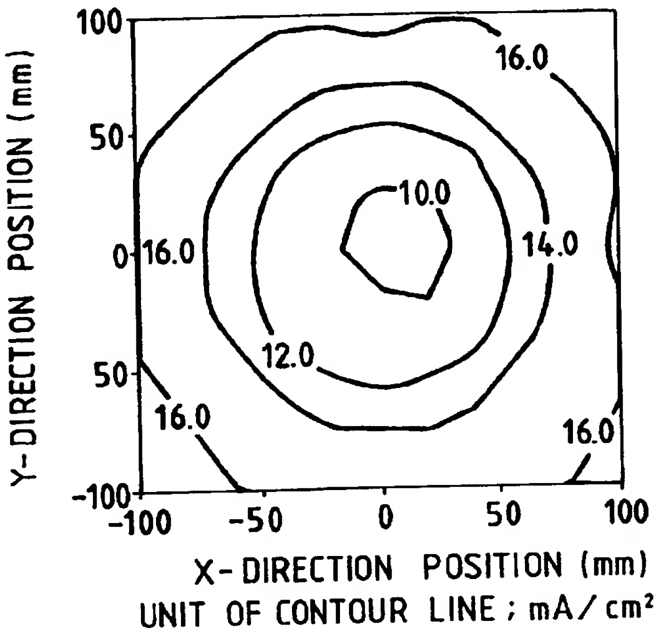

100
50
0
50
-100
-100
-50
0
50
100
16.0
10.0
14.0
16.0
12.0
16.0
16.0
Y-DIRECTION POSITION (mm)
X-DIRECTION POSITION (mm)
UNIT OF CONTOUR LINE ; mA/cm²

FIG. 4(b)

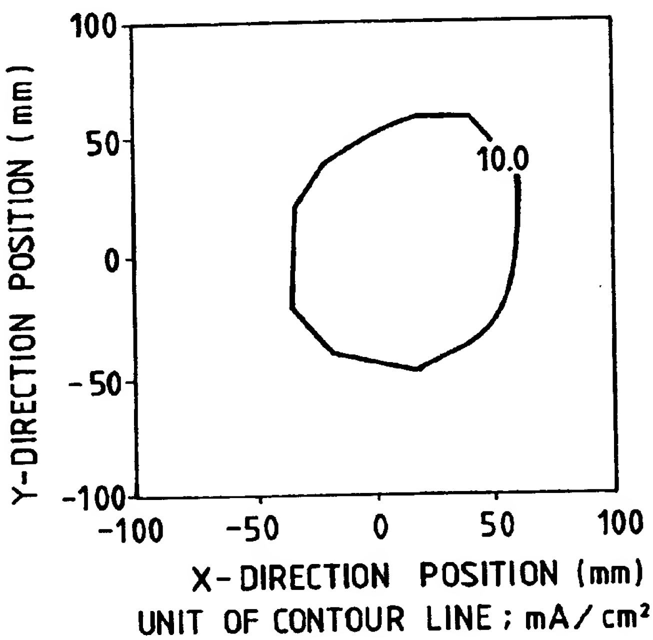

100
50
0
-50
-100
-100
-50
0
50
100
10.0
Y-DIRECTION POSITION (mm)
X-DIRECTION POSITION (mm)
UNIT OF CONTOUR LINE ; mA/cm²

FIG. 5

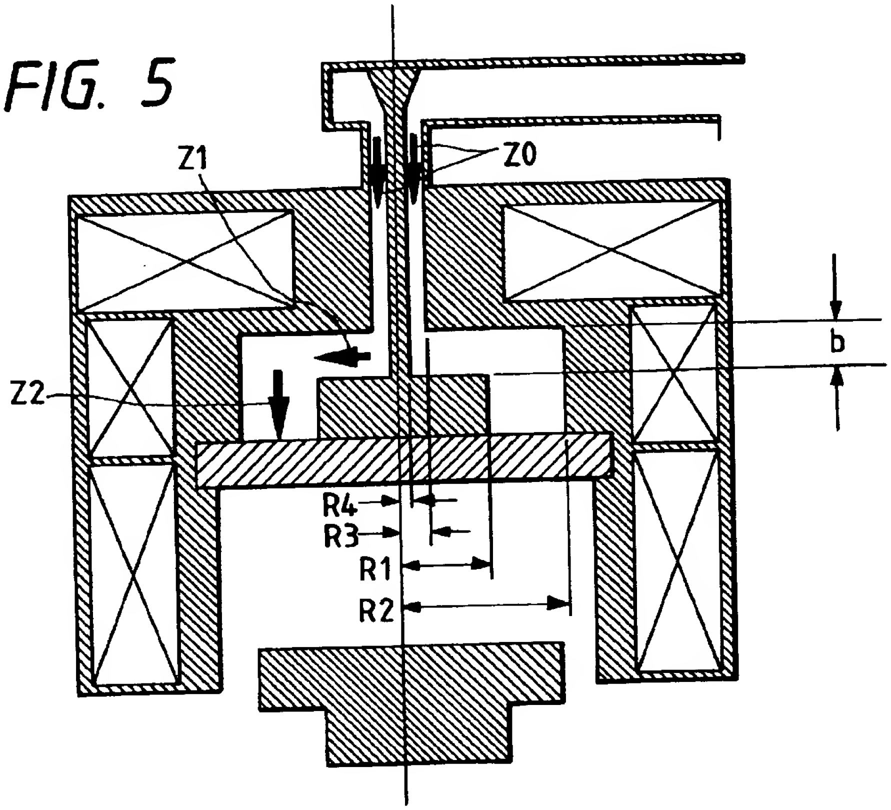


FIG. 6

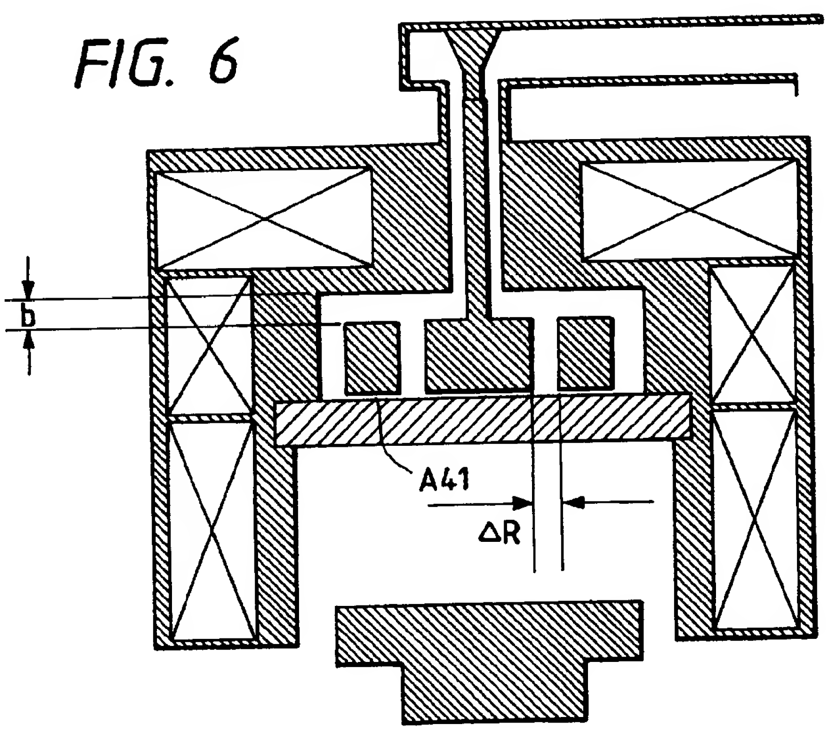


FIG. 7

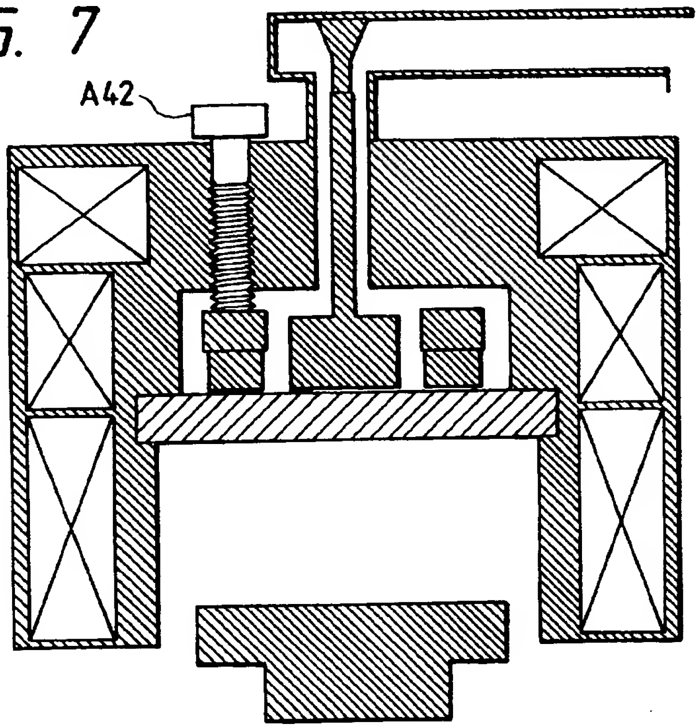


FIG. 8

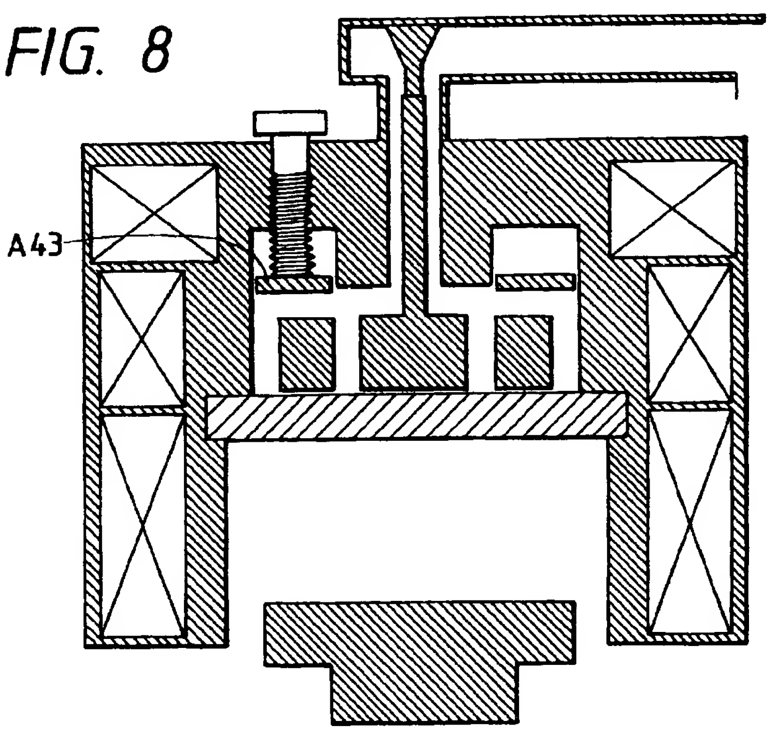


FIG. 9

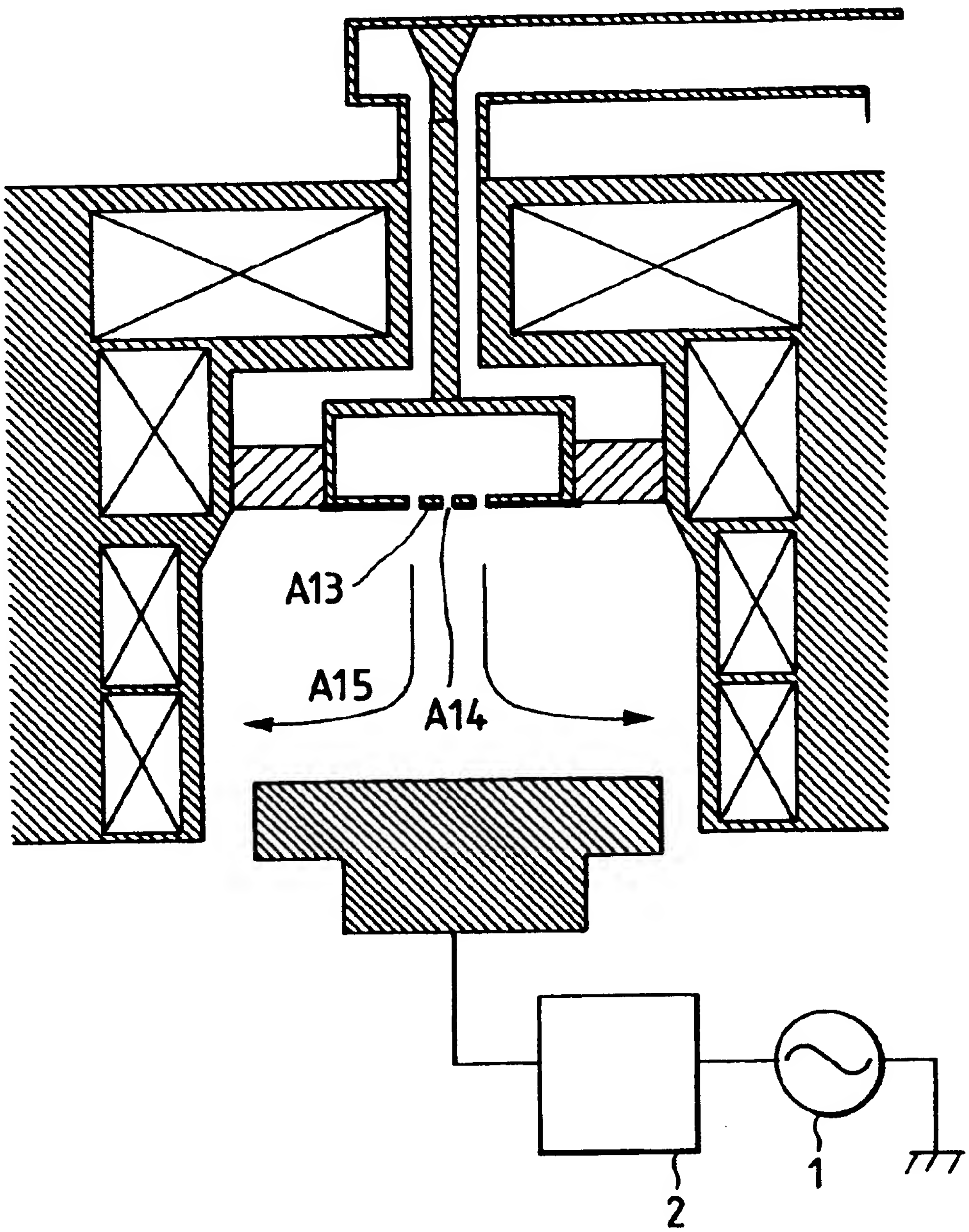


FIG. 10(a)

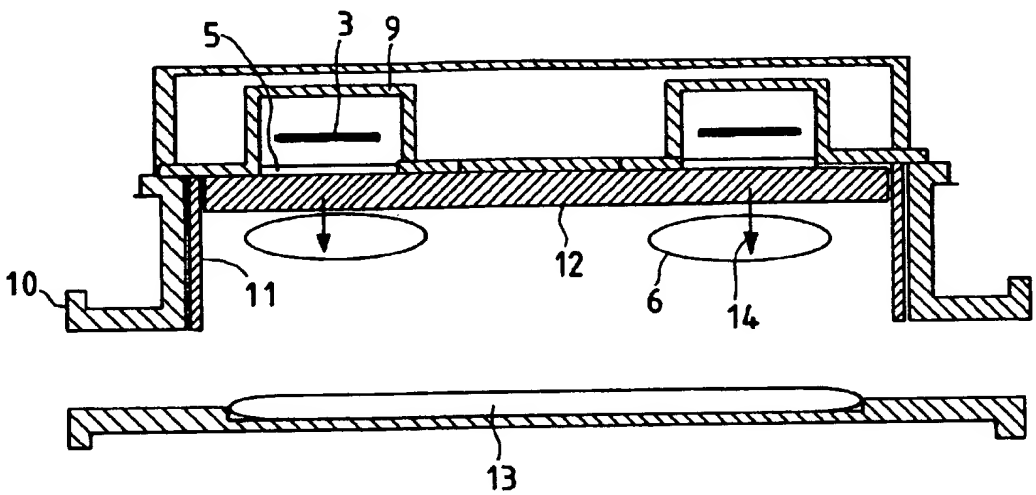


FIG. 10(b)

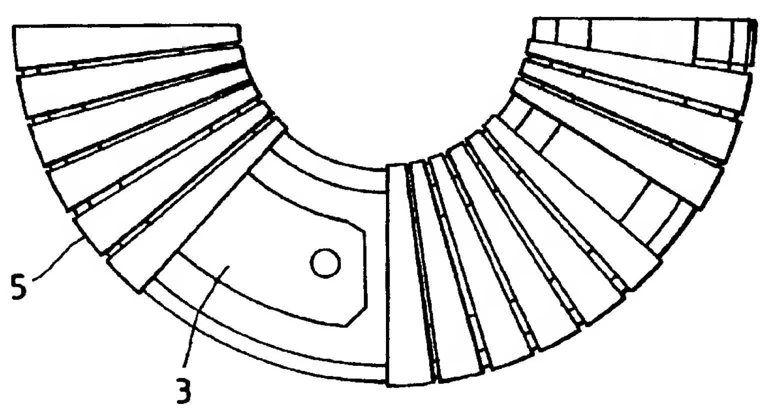


FIG. 11

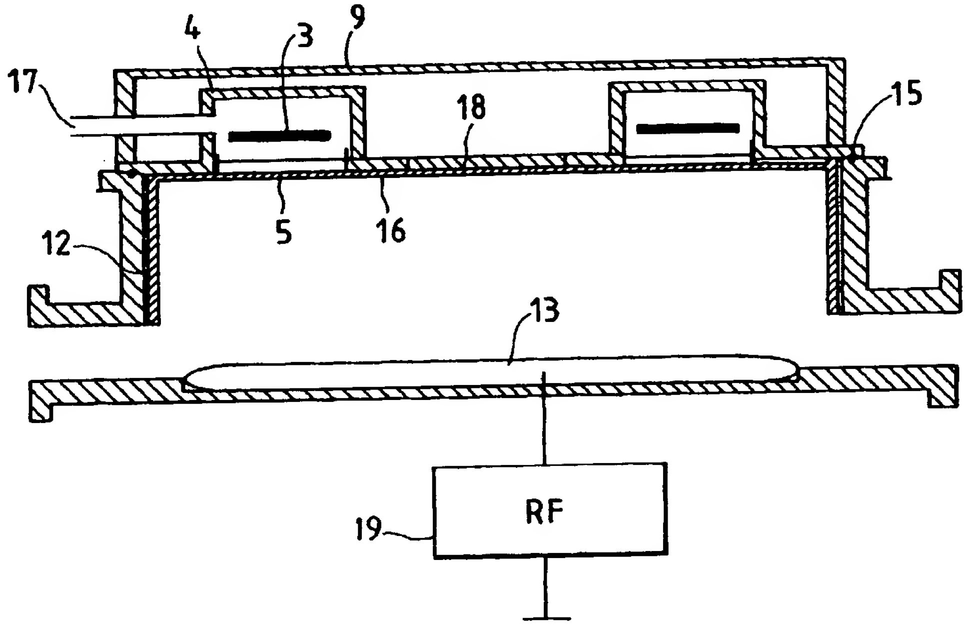


FIG. 12

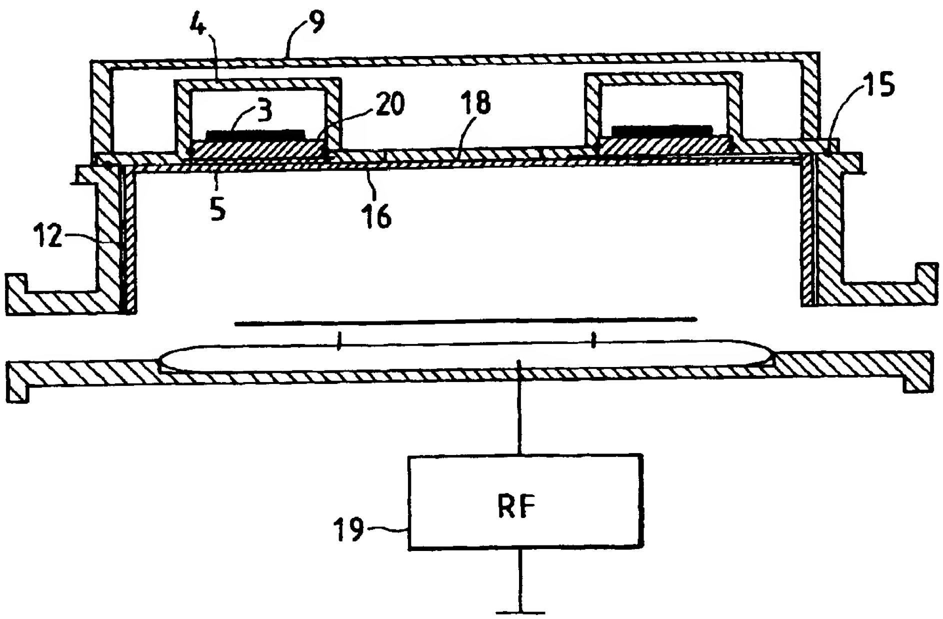


FIG. 13

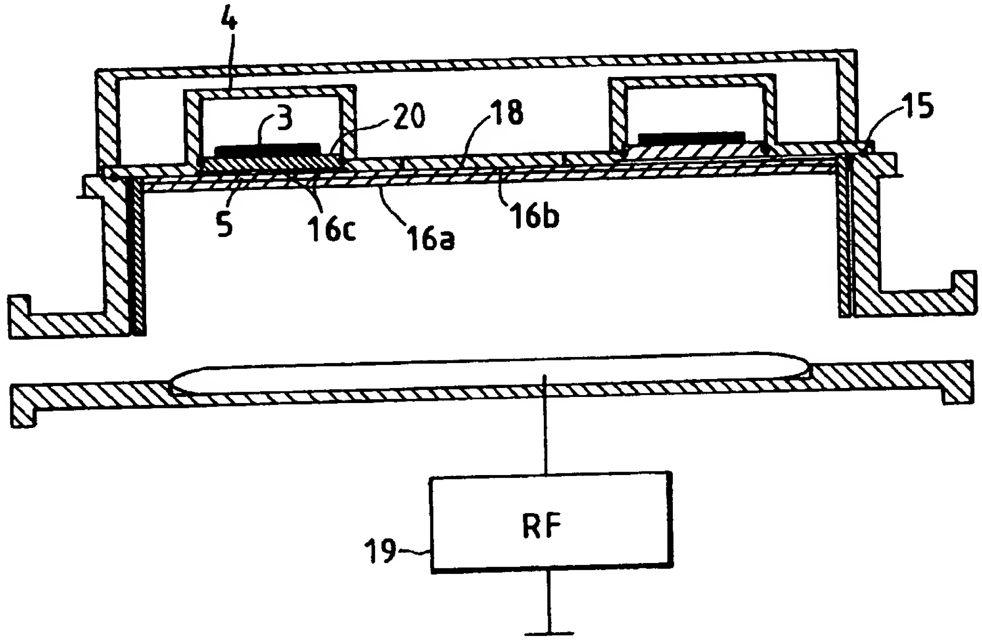


FIG. 14

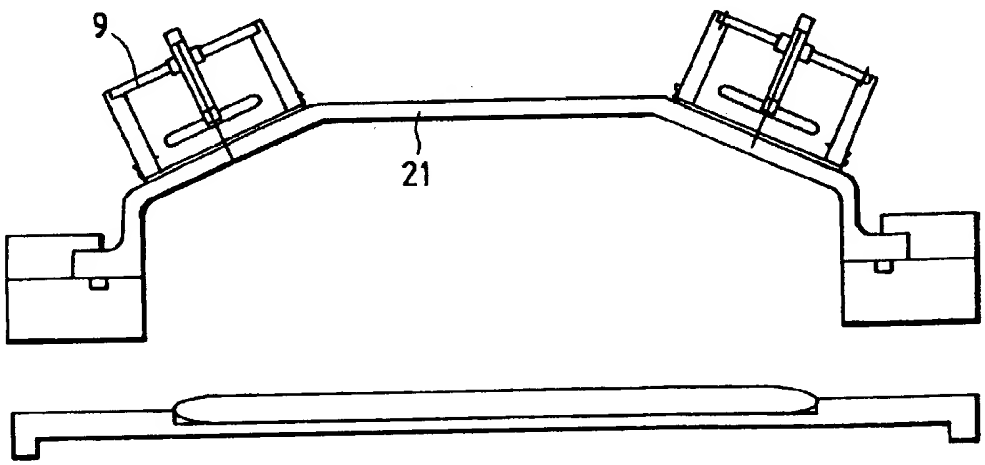


FIG. 15

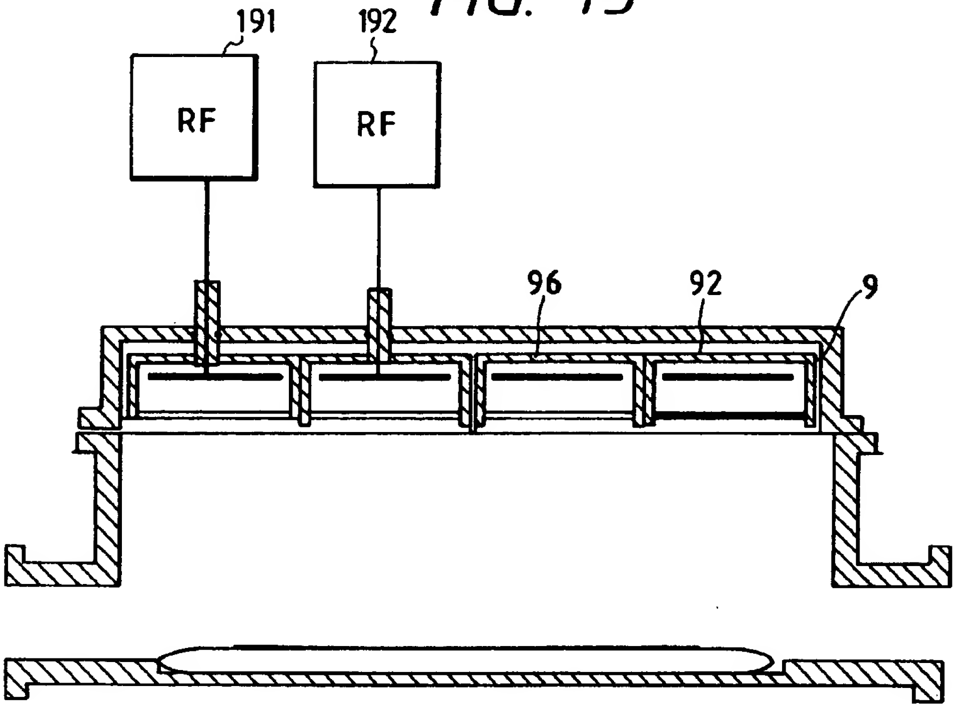
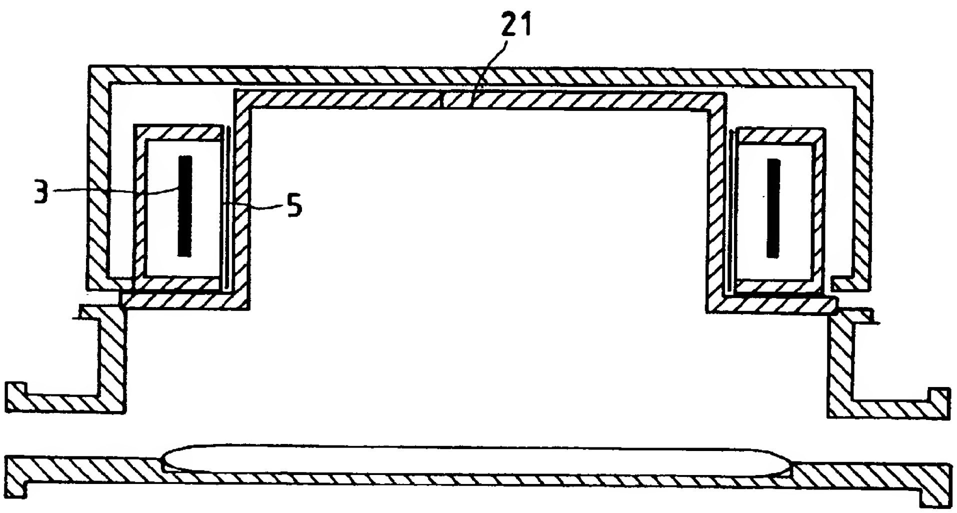


FIG. 16



METHOD AND APPARATUS FOR PLASMA PROCESSING APPARATUS

CROSS REFERENCE TO RELATED APPLICATION

This is a divisional of U.S. application Ser. No. 08/649,190, filed May 17, 1996, now U.S. Pat. No. 6,034,346 the subject matter of which is incorporated by reference herein.

BACKGROUND OF THE INVENTION

The present invention relates to plasma processing methods and apparatus, and more particularly to a plasma processing method and apparatus fit for processing a specimen, such as a semiconductor substrate (hereinafter called a "wafer"), by generating a plasma using a microwave and a high-frequency wave in the frequency range of 10 to 100 MHz.

In the case of apparatus in general for generating a plasma by introducing a microwave into a process chamber, the uniformity of plasma density distribution above a wafer surface to be treated is particularly important in securing a desired uniformity of processing, such as etching. In order to deal with this problem, there has been proposed a method of radiating a microwave in a ring-like shape from the top surface of a process chamber to generate a ring-shaped plasma, so that uniform plasma distribution is obtained on the surface of a wafer, as mentioned in, for example, Document A, "The Japan Society of Applied Physics, 1994, Autumn, 19p-ZV-4" or Document B, "The Japan Society of Applied Physics, 1994, Autumn, 19pZV-6." This is because the plasma tends to diffuse as it is moved from its originating place in the direction of the wafer. Although a desired uniformity of the etching rate itself is ultimately required, it may be desirable for the apparatus also to have a density distribution adjusting means, since the plasma density distribution is concave or convex, rather than a uniform distribution.

Moreover, another means for generating a ring-shaped plasma is described in, for example, Japanese Patent Laid-Open No. 112161/1994.

On the other hand, an inductively coupled RF (high frequency) plasma source as representatively disclosed in Japanese Patent Laid-Open No. 79025/1991, has been in frequent use recently as a plasma source for CVD and etching. This plasma source has made possible not only a high density (10^{11}–10^{12} cm^{-3}) but also a low-pressure (1–10 mTorr) action equivalent to what is offered by a microwave ECR plasma source, though it is compact in construction. Even in this system, however, it is still required to provide a definite means for securing a desired plasma uniformity and to solve a problem arising from foreign matter produced by wall-surface sputtering, which will be described below, as in the case where a microwave is used.

First, a description will be given of a problem concerning microwave plasma uniformity herein. The ring-shaped plasma radiation means according to the above-described Documents A and B has been arranged so that it is fit for use in producing a uniform plasma, but the ultimate plasma density thus attained thereby remains at a low level, such as 3–10×10^{10} cm^{-3} and still fails to reach the following level which is industrially required 3–10^{-11} cm^{-3} or greater.

This is considered attributable to the fact that, in both the cases mentioned above, the absorption efficiency of a microwave has not been optimized, because a local magnetic field produced by a permanent magnet is employed at an outlet for the microwave, nor has the design of a microwave transmission path for large electrical power to be transmitted. According to the above-referenced Document A, the introduction of a complicated three-dimensional structure into the plasma processing chamber may cause foreign matter to be produced. Japanese Patent Laid-Open No. 112161/1994 describes an arrangement in which a coaxial waveguide is opened in a tapered shape, which results in rendering a microwave radiating portion large-sized.

A description will subsequently be given of a problem concerning plasma uniformization and foreign matter control in the case of a high-frequency wave.

The aforementioned system (Japanese Patent Laid-Open No. 79025/1991) has presented problems, including the need for the inner surface of a vacuum chamber to be scraped down as a result of sputtering due to ion bombardment, thus increasing not only the production of foreign matter, but also increasing the frequency at which parts need to be replaced in the vacuum chamber; and, in addition, there is lowering of the plasma uniformity as the plasma tends to concentrate at the center of the chamber and so forth.

In this case, the induction coil placed outside the vacuum chamber undergoes partial electrostatic coupling with the plasma, rather than the intended inductive coupling therewith, and ions are accelerated by this electrostatic coupling toward the inner surface of the vacuum chamber, whereby the sputtering of the inner surface is said to occur. Consequently, an attempt was made to remove the electrostatically coupled component by introducing an electrostatic shield, called a Faraday shield, between the induction coil and the vacuum chamber so as to suppress the sputtering. However, the effect of this arrangement is not perfect and there still remains a scraping problem because of the sputtering: (e.g., Y. Hikosaka et al., "Free Radicals in an Inductively Coupled Etching Plasma," Jpn. J. Appl. Phys. Vol 133 (1994) pp 2,157–2,163 Part 1. No. 4B, April 1994).

In the system disclosed in Japanese Patent Laid-Open No. 79025/1991, further, a plasma generating area over the whole top surface of the chamber and the aforementioned plasma diffusion effect have been combined to cause the plasma to be centralized.

Moreover, another problem pertaining to the plasma processing apparatus (Japanese Patent Laid-Open No. 79025/1991) has arisen from the ignitability and stability of plasma. When the induction system is used to ignite a plasma, it is necessary to form the top surface of the process chamber with dielectric material so as to introduce the magnetic flux generated by the induction coil into the process chamber. For this reason, the thickness of the dielectric material needs to be increased (i.e., in order to have vacuum force maintained), which results in sharply worsening ignitability and stability of the plasma as the distance between the induction coil and the top surface of the plasma is increased.

A third problem is concerned with the fact that the structure makes it difficult to have a grounding electrode set in parallel and opposite to a specimen, since a thick dielectric material has to be employed. Although an attempt has been made to increase the processing accuracy normally by applying a high-frequency bias to a specimen-holding stage in the case of an etcher or CVD, the processing tends to lack uniformity in the absence of such a grounding electrode positioned in parallel and opposite to the specimen; that is, in a case where the grounding electrode is positioned on the side wall of the chamber, the length of the high-frequency bias circuit portion which is allowed to pass through the plasma differs between the center of the wafer and the outer

periphery of the wafer. Thus, the bias is unevenly applied to the wafer, and, especially when the wafer has a large diameter (8→12 inches), this problem becomes conspicuous.

A fourth problem originates from a variety of bad effects, including an abnormal discharge resulting from the high input impedance of the induction RF coil, which makes the power supply terminal have a high voltage, an unstable discharge resulting from sputtering and improper matching as electrostatically coupled components go on increasing, an impediment to the ignitability and so on.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a plasma processing method and apparatus, which is capable of generating a high-density plasma at an industrially required level by generating a uniform plasma and simultaneously transmitting large electric power through compact, ring-shaped microwave radiation means and of adjusting the uniformity on a wafer surface.

Another object of the present invention is to provide a plasma processing method and apparatus so configured as to prevent any foreign matter from being produced in a process chamber and which is capable of adjusting uniformity on a wafer surface; and more particularly to provide an electromagnetically coupled plasma processing apparatus based on a novel principle according to which the following four problems, associated with a high-frequency plasma, can be solved simultaneously or partially:

(1) improvement of sputtering reliability by removing electrostatically coupled components;

(2) setting of a plasma close to an RF antenna;

(3) installation of an opposed grounding electrode; and

(4) lowering of coil impedance.

To achieve the above objects, during plasma processing of a specimen, the density distribution of the plasma is independently controlled.

Preferably, the density distribution of the plasma is independently controlled by a position adjustment of an ECR or a magnetic field gradient.

Further, preferably, the density distribution of the plasma is controlled on the basis of the kind of material of the specimen.

Further, preferably, the specimen is uniformly processed by independently controlling a plasma density distribution, a gas distribution and a bias distribution.

To achieve the above objects, a plasma processing apparatus comprises a microwave introducing device, a magnetic field coil for generating a static magnetic field, a process chamber for generating a plasma using an introduced microwave, a gas supplying device for supplying a gas to the process chamber, a specimen stage for holding a wafer, and a vacuum evacuating device for evacuating the process chamber, the apparatus being characterized in that the microwave introducing device is arranged to transmit a microwave in the coaxial TEM mode.

Preferably, a plasma processing apparatus comprises a microwave introducing device, a magnetic field coil for generating a vertical static magnetic field, a process chamber for generating a plasma using an introduced microwave, a gas supplying device for supplying a gas to the process chamber, a specimen stage for holding a wafer, and a vacuum evacuating device for evacuating the process chamber, the apparatus being characterized in that the microwave introducing device is equipped with a coaxial waveguide converter, a small-diameter waveguide, a discoid parallel-plate waveguide, an enlarged coaxial waveguide and a microwave introducing vacuum window.

Preferably, R_1, R_2, R_3, R_4 and b are selected so that a small-diameter coaxial waveguide characteristic impedance Z_0 (=601n(R_3/R_4), R_3: in-coaxial-tube conductor radius, R_4: out-of-coaxial-tube conductor radius) coincides with an impedance Z_1 (=60b/R_3, b: parallel disk distance) of the disk-shaped waveguide at a junction with the disk-shaped waveguide, and so that an enlarged coaxial waveguide impedance Z_2 (=601m(R_2/R_1-), R_2: out-of-coaxial-tube conductor radius, R_1: in-coaxial-tube conductor radius) coincides with an impedance Z_1 (=60b/R_1) of the disk-shaped waveguide at a junction with the disk-shaped waveguide.

Preferably, an outer diameter R_2 of the enlarged coaxial waveguide is smaller than an inner diameter R_5 of the process chamber connected to the microwave vacuum window ($R_2<R_5$).

Preferably, a microwave has a frequency between 500 MHz and 5 GHz.

Preferably, a plurality of microwave sources of different frequencies are used at the same time.

Preferably, a variable frequency microwave source is used.

Preferably, in a vacuum window portion, a plasma contact portion of the portion other than a portion ($R_1<R<R_2$) equivalent to a microwave radiating part is provided with a grounding conductor plate or a semiconductor plate, such as Si or SiC.

Preferably, a magnetic field coil or a permanent magnet is provided by utilizing a portion other than a portion ($R_1<R<R_2$) equivalent to a microwave radiating part.

Preferably, the discoid parallel-plate waveguide includes two small- and large-diameter ring-shaped opening portions and the enlarged coaxial waveguide is connected to each of the opening portions.

Preferably, the enlarged coaxial waveguides include means for varying microwave power distributed to them.

In reference to the aforesaid second object group, that is, the provision of means for securing uniformity in a high-frequency inductive plasma and for removing wall-surface sputters, an electromagnetically coupled Rf antenna system in place of an inductively coupled RF coil is employed according to the present invention. The RF antenna comprises a central conductor for letting a high-frequency current flow into a closed space surrounded with a conductor and a slit situated on one side of the closed space facing the plasma, the slit being ingeniously opened so as not to look directly at the plasma on the central conductor. The central conductor and the closed space form a cavity resonator for electromagnetically creating a resonance condition. An electromagnetic wave leaking from the cavity resonator via the slit propagates into and generates the plasma. Such an electromagnetic coupling system using a resonant cavity makes it possible to obviate completely and theoretically the generation of an electrostatically coupled component commonly observed in the prior art and to solve the problem of sputtering and wall scraping, for example. At the same time, a construction so designed so as to solve the four problems enumerated previously can be attained through this coupling system.

Preferably, the antenna system is to be installed not beyond but on this side of a dielectric window constituting a vacuum chamber.

Preferably, a slit conductor is potentially switchable from floating to a grounding potential and vice versa.

A plasma generation area will be located directly below a ring radiation source and a ring-shaped plasma will be

generated if a microwave in a coaxial ring-like shape is radiated so as to regulate the intensity (B=875 gausses when a microwave of 2.45 GHz is employed) of a static magnetic field for use in causing electron cyclotron resonance (ECR). Since the plasma diffuses, it is evenly distributed when it is conveyed to the wafer surface.

If the intensity of microwave radiation from the respective ring-shaped sources is changed by altering the diameters of the coaxial rings or providing a double ring radiation source, the plasma uniformity may be varied. In other words, the plasma distribution will have a heavier concentration at the center of the wafer if the intensity of the radiation is strengthened on the inner peripheral side of the double ring radiation source and a heavier concentration on the outer periphery of the wafer if the intensity is strengthened on the outer peripheral side thereof.

If an ECR position is lowered so that a microwave cannot be absorbed by a plasma immediately after the microwave leaves the ring radiator, the microwave strength distribution diffuses and is then absorbed by the plasma, so that the plasma uniformity above the wafer surface becomes variable. In other words, the uniformity can also be changed by changing the static magnetic field strength.

In accordance with the present invention, when the ring-shaped microwave radiating source is installed on an atmospheric side via the vacuum introducing window, the likelihood of the occurrence of foreign matter caused by the radiating source itself is eliminated.

Since the ring radiator is employed, it is possible to install a wafer-opposed electrode in the central portion of the radiator. Specifically, a conventional type of ECR microwave plasma processing apparatus has a structure in which it is difficult to install an electrode at a position opposing the wafer, so that it is difficult to apply a high-frequency bias uniformly, but the present invention makes it possible to solve this conventional problem. In the central portion, it is possible to install a gas pipe for discharging a processing gas or a member for absorbing the excess radicals contained in a processing plasma (for example, a Si plate scavenger for fluorine radicals).

If the microwave radiating source is installed at a position spaced away from the inner side wall of the plasma processing chamber, the plasma generation position does not directly touch the wall, so that it is possible to keep out foreign matter due to the accumulation of high-degree dissociated radicals or prevent damage to a side wall material.

A high-frequency type plasma will subsequently be described.

First, a detailed description will be given of the principle of the aforementioned electromagnetically coupled plasma generation by reference to the drawings.

FIG. 2(*a*) is a diagram illustrative of the principle of the invention. As shown in FIG. 2(*a*), an RF power supply **1** is connected via a matching box **2** to a loop antenna body **3**. The loop antenna is surrounded by a cavity resonator **4** on all sides and slits **5** are opened in only the side which faces a plasma. As shown by a vertical sectional view of FIG. 2(*b*), two layers of slits **5** are alternately arranged so that they are not overlapped, whereby only the electromagnetic wave components radiated from the antenna can be propagated toward a plasma without making the antenna body **3** look directly at the plasma. A detailed description will further be given of this situation. In reference to FIGS. 2(*a*), 2(*b*), it is assumed that an alternating current I is caused to flow through an antenna conductor. A return current I' passes through the side and back plates of the cavity resonator, which are screwed down with screws, on its way back. (No current flows through the slits since no flow channel is formed therein). An alternating-current magnetic field H is created by the antenna current I and the return current I', and part of the magnetic field leaks out via the slits. Because of the magnetic field that has leaked outside, a ring-shaped electromagnetic field E and other electromagnetic fields (not shown) are successively formed on a plane perpendicular to the magnetic field, in accordance with the Maxwell's law of radio-wave propagation, and are transmitted in the direction of a plasma **6**. Thus only the electromagnetic wave component radiated from an antenna chamber in a closed space is coupled to the plasma according to the present invention, and a spurious component, such as an electrostatically coupled component and the like radiated from a single antenna body, is never radiated generally. As the sputtering of a structural member caused by abnormal discharge or abnormal ion acceleration is preventable, a reliable plasma source can be formed.

Another (second) advantage of the closed space structure formed by the cavity resonator is as follows: Even though a metal conductor is installed in a space other than a closed one, the radiation of the radio wave toward the plasma is not essentially affected. When a conductor plate is inadvertently placed close to the prior art induction coil, magnetic flux is blocked off at that place and the problem is that no plasma can be generated in this case. However, this problem is solvable according to the present invention; in other words, the structure according to the present invention is advantageous in that the opposed grounding electrode is readily installed.

Still another (third) advantage of the closed space structure formed by the cavity resonator is that the input impedance of an antenna is reducible. The antenna impedance of the prior art induction coil is roughly determined by the inductance L of the coil, which is turned out to be $j\omega L$ (ω=angular frequency). In the closed space structure, the antenna module forms a kind of coaxial distribution constant line and the impedance is given by the following equation:

$$Z=(L+C)^{1/2}$$

C in this equation represents the capacitance between the central conductor and the inner wall of the cavity resonator, wherein C can be set greater; consequently, the impedance can be set smaller through proper structural design. Simultaneously, the value of L can be set smaller and the impedance can also be set smaller, since it is feasible to form the central conductor into a flat shape. Since this arrangement is based on a distribution constant system, the terminal impedance can be brought close to pure resistance on condition that the antenna length (effective) and the applied frequency are properly chosen, so that impedance matching is facilitated. According to the closed space structure formed by this cavity resonator, there is a further (fourth) important advantage. More specifically, the closed space structure demonstrates a definite effect resulting from securing plasma uniformity and this will be described by reference to the drawings. FIG. 3(*b*) shows an improved version of the prior art, which is readily presumable, wherein a method of winding the Rf coil has been changed in that peripheral winding is adopted, so as to generate a ring-shaped plasma. FIG. 3(*c*) refers to a cavity resonance system according to the present invention.

As already described, the induced electric field E formed under the electromagnetic induction law is deviated toward the center since the pattern of a magnetic line of force H generated by each induction coil **3** is also deviated toward

the center according to the prior art arrangement of FIG. **3**(*a*), so that no uniform plasma can be produced. As shown in FIG. **3**(*b*) then, it is possible to supply current to the coils **3**, which are now separated from each other but this is still unsatisfactory. Even when the coils are thus separated, the magnetic line of force H that has been formed passes through the center of the chamber, whereby a strong induced electric field E is still formed in the vicinity of the center. The magnetic line of force formed as shown in FIG. **3**(*c*) has a different pattern. The presence of the cavity resonator **4** surrounding an antenna conductor **3** has the magnetic line of force H confined within the cavity resonator and consequently the plasma generation area becomes ring-shaped directly below the antenna. In the course of isotropic diffusion onto the specimen wafer, the plasma is ultimately averaged and uniformized as anticipated. In other words, the cavity resonance system according to the present invention makes it possible for the first time to generate a ring-shaped plasma and irradiate a specimen uniformity with the plasma.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a partial front elevational view showing in longitudinal section a first embodiment of the present invention.

FIGS. **2**(*a*) and **2**(*b*) are diagrams showing the principle of the present invention.

FIGS. **3**(*a*), **3**(*b*) and **3**(*c*) are diagrams showing the principle of the present invention.

FIGS. **4**(*a*) and **4**(*b*) are graphs showing plasma test results according to the present invention.

FIG. **5** is a view similar to FIG. 1 showing the dimensional relationship of the present invention.

FIG. **6** is a partial front elevational view showing in longitudinal section a second embodiment (1) of the present invention.

FIG. **7** is a view similar to FIG. **6** showing a another variation of the second embodiment of the present invention.

FIG. **8** is a view similar to FIG. **6** showing another variation of the second embodiment (3) of the present invention.

FIG. **9** is a partial front elevational view showing in longitudinal section a third embodiment of the present invention.

FIG. **10**(*a*) is a side sectional view and FIG. **10**(*b*) is a bottom plan view showing a fourth embodiment of the present invention.

FIG. **11** is a partial front elevational view showing in longitudinal section a fifth embodiment of the present invention.

FIG. **12** is a partial front elevational view showing in longitudinal section a sixth embodiment of the present invention.

FIG. **13** is a partial front elevational view showing in longitudinal section a seventh embodiment of the present invention.

FIG. **14** is a partial front elevational view showing an eighth embodiment of the present invention.

FIG. **15** is a partial front elevational view showing in longitudinal section a ninth embodiment of the present invention.

FIG. **16** is a partial front elevational view showing in longitudinal section a tenth embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention will be described below by reference to an embodiment. FIG. **1** is a partial front elevational view showing in longitudinal section a plasma processing apparatus according to one embodiment of the present invention. In FIG. **1**, a microwave is transmitted through a waveguide **A1** and transfers to a coaxial TEM mode in a coaxial waveguide converter **A2** before being conducted through a small-diameter coaxial tube **A3**. The microwave leaves the coaxial tube **A3** and transfers to a parallel disk waveguide **A4**. After having radially enlarged, the microwave transfers to a large-diameter coaxial tube portion **A5** and enters a process chamber **A6**. The process chamber is surrounded by electromagnetic coils **A7** for generating static magnetic fields, thus forming an ECR plane **A8**. A plasma generating portion **A9** assumes a ring shape corresponding to this ECR plane and the plasma is uniformized above a wafer installation electrode **A10**. In FIG. **1**, reference numeral **A11** denotes a vacuum sealing microwave introducing window which is made of quartz or the like. FIG. **4**(*a*), **4**(*b*) shows the result obtained by examining the condition in which a plasma is generated under this system. FIG. **4**(*a*), **4**(*b*) refers to the consequence of two-dimensional distribution measurement on a saturated ion current density (equivalent to a plasma density directly above the wafer) at a position above the electrode (in FIG. **4**(*a*), the ECR plane: 79 mm above the wafer; and in FIG. **4**(*b*), the ECR plane: 99 mm above the wafer), wherein thorough uniformity or concave distribution is seen to become obtainable depending on the magnetic field condition. The current density thus obtained is as high as 10 mA/cm^2 or above in the case of a C_4FB plasma and reaches the equivalent level required. The input microwave power was 1–2 kW and the waveguide was not overheated, for example.

The dimensional specifications of such a microwave radiator will subsequently be described by reference to FIG. **5**. A small-diameter coaxial tube characteristic impedance Z_0=50 Ω, a parallel disk impedance $Z_1(R)$ and an enlarged coaxial portion impedance Z_2 need to conform to each other so that the reflection of a microwave is prevented from occurring at each junction. The impedance Z_1 was newly derived as there was no publicly known document about it. The result is as follows:

$$Z_1(R) = \frac{bZ_0}{2\pi jR} \cdot \frac{Y_0^2(KR)}{Y_1^2(KR)}$$

where b: disk-to-disk distance, R: radial position, 70=377 Ω, j: imaginary unit, Y_1^2: linear Hankel function of the second kind, and K=2π/λ; wave number, input wavelength.

If KR>1, $Z_1(R)$ asymptotically approximates to

$$Z_1(R)=Z_0b/2\pi R=60b/R$$

The impedance Z_2 of the enlarged coaxial portion is expressed as

$$Z_2=601n\ R_2/R_1$$

Therefore, the unknowns R_1, R_2, R_3, R_4 and b may be determined so that $Z_0=Z_1(R_3)$ and $Z_2=Z_1(R_1)$ are obtained.

FIG. **6** shows a second embodiment of the present invention. It is desirable that plasma uniformity is made adjustable over the range of perfect uniformity to convex and concave uniformity. This means that the etching uniformity of a specimen to be processed is made controllable by the uniformity of processing gas and a high-frequency bias other than the plasma uniformity and that the plasma uniformity is set to be adjustable so as to cover the influence of any other uniformity determining factor to ensure that final etching

uniformity is secured. FIG. 6 shows an arrangement in which the ring radiation part is provided as two rings so that a microwave is emitted from each of the inner and outer peripheral rings. By changing the disk distance b and an opening diameter ΔR of the inner peripheral ring, the distribution of power varies and so does the distribution of the microwave within the process chamber. To change ΔR, a disk component **A41** may be replaced. Otherwise, b may be changed by operating a screw mechanism **A42** from above, as shown in FIG. **7**, or a ceiling member **A43** for the parallel disk may be set to be variable by means of a plunger mechanism, as shown in FIG. **8**. The system of FIG. **6** makes it necessary to replace the parts each time the uniformity is changed. However, the waveguide is simpler and more reliable than those shown in FIGS. **7** and **8**. Although the efficiency of adjusting the uniformity is conversely improved in the examples shown in FIGS. **7** and **8**, the movable parts located in the waveguide raises a reliability problem at the time large power is passed therethrough.

FIG. **9** shows a third embodiment of the present invention, wherein an electrically conductive structure (Al or the like) is introduced on the bottom side of the parallel disk facing the process chamber A to form an electrode **A13** which is opposed with respect to the wafer. This arrangement is intended to improve the uniformity of high-frequency bias. The use of Si or SiC for a member at this position allows the excess fluorine contained in the plasma to be absorbed, so that the underlying layer (Si) selectivity in an SiO_2 etching process is made improvable thereby. A processing gas blowing mechanism **A14** using this space is provided according to the present invention in anticipation of processing gas uniformity by utilizing a processing gas flow **A15** from the central portion toward the peripheral portion. Moreover, a magnet (coil or permanent magnet) or a magnetic body **A16** can be installed in this space and a magnetic-line-of-force structure **A17** is also disposed, as shown in FIG. **9**, whereby the plasma uniformity can be increased.

A description will subsequently be given of various examples of a high-frequency plasma system. FIGS. **10**(*a*) and **10**(*b*) show a fourth embodiment of the present invention. In FIG. **10**(*a*), a process chamber **10** comprises a cylindrical side wall **11**, a quartz ceiling panel **12** and a specimen- holding stage **13**. Ring-shaped antenna modules **9** are placed on the surface of the quartz ceiling panel **12**. The antenna module **9** includes a loop antenna **3**, a cavity resonator **4**, a slit **5** and the like. The radio wave **14** emitted from the cavity resonator **4** is radiated as shown by an arrow of FIG. **10**(*a*), thus causing a plasma **6** to be generated. As the plasma diffuses, it becomes a uniform plasma over the whole surface of a specimen when it reaches the specimen-holding stage **13**.

FIG. **10**(*b*) is a bottom plan view taken from under the antenna module **9**, wherein part of a double-layer slit **5** is removed to make the antenna body **3** visible.

FIG. **11** shows a fifth embodiment of the present invention. In general, it is preferred for the distance between an antenna module and a plasma to be shorter in the case of an electrode-coupled plasma in view of the ignitability of the plasma. According to the prior art, however, the electrostatically coupled component simultaneously increases, which also poses a problem of abnormal ion acceleration, and consequently the antenna could not be placed near the plasma.

Since an electrostatically coupled component is never generated according to the present invention, the antenna can be set sufficiently close to the plasma and the ignitability can thus be increased. In FIG. **11**, the cavity resonator **4** is also used as a vacuum boundary and coupled to the process chamber body **12** with an O-ring **15**. A cover **16** (made of quartz, alumina ceramics or sapphire) is fitted to the front of the antenna module lest the plasma is directly exposed to heavy metal. In order to avoid the ignition of the plasma in the cavity resonator in a vacuous condition, an exhaust port **17** is provided separately, and by means of differential exhausting, the cavity resonator is kept under extreme vacuum to prevent discharging therein.

In the fifth embodiment of the invention, as seen in FIG. **12**, other secondary important effects are brought about. When the plasma processing apparatus is applied to etching or a sputter CVD apparatus in general, a high frequency **19** of a system different from what is intended for generating a plasma is applied to the specimen-holding stage to apply self-bias to the specimen so as to draw ions in the plasma onto the surface of a specimen perpendicularly for the purpose of improving the specimen processing accuracy and processing rate. In the prior art, however, the distance between a high-frequency circuit and the center of the specimen through the plasma differs from the distance between the circuit and the end portion of the specimen because a conductor to be used as the opposed grounding electrode of the circuit of the second high frequency **19** forms the inner side wall **12** of the process chamber; consequently, uniformity in processing has been unachievable because the impedance remains unequal. In order to prevent lack of uniformity in processing, it is preferred for a parallel, flat plate-like grounding electrode to be placed opposite to the specimen. However, such an electrode could not be placed in the way stated above in the prior art because the inductively coupled high-frequency plasma intercepted the induced magnetic flux. According to the present invention, the antenna module and the metal ceiling panel **18** of the inner wall of the antenna module face the plasma via a sufficiently thin cover **16**, which is capable of functioning as an opposed grounding electrode set in parallel to the whole surface of the specimen, so that processing uniformity is improved. (Regarding the high-frequency circuit, the impedance of a capacitor element will be sufficiently low if the cover **16** is thin. Thus the conductor **18** can be made to function as a grounding electrode. When a high frequency of 13.56 MHz is used as the second high frequency **19**, for example, a cover of quartz not greater than 3 mm thick may be satisfactory).

FIG. **12** shows a sixth embodiment of the present invention. According to this embodiment of the present invention, an insulating spacer **20** formed of quartz, alumina ceramics or the like is inserted between the antenna body **3** and an antenna exit **5**. This spacer is hermetically fitted with respect to the cavity resonator **4** or sealed under vacuum by means of an O-ring. Consequently, the differential exhausting described with reference to FIG. **3** according to one embodiment of the present invention can be dispensed with and the structure simplified.

According to this embodiment of the invention as noted in the summary of the invention, the antenna which brings about another secondary effect constitutes a constant circuit of distribution and this makes it desirable to lower the impedance of the line with a view toward increasing the current and lowering the voltage because coupling with the plasma is improved by increasing the current and because an abnormal discharge around the antenna is impeded by lowering the voltage. The impedance of the line is determined by the characteristic inductance L and characteristic capacitance C of the line and is given by the following equation:

$$Z=(L+C)^{1/2}$$

Since C is determined by the capacitance between the antenna body 3 and the slit conductor 5, C can be increased and therefore Z can be decreased by setting the antenna body 3 closer to the slit conductor 5 to the extent that discharge breakdown is not caused and the dielectric constant between the antenna body 3 and the slit conductor 5 is increased; a dielectric spacer 20 made of quartz, alumina or the like may preferably be inserted between the antenna body 3 and the slit conductor 5 for this purpose.

FIG. 13 shows a seventh embodiment of the present invention. According to this embodiment of the invention, the slit portion 5 of the cavity resonator 4 is replaced with two sheets of cover glass 16*a*, 16*b* and Al or Au vapor deposition 16*c* is utilized for forming a slit pattern on each sheet of cover glass. Thus, the slit conductors in FIGS. 11, 12 can be disused with the effect of not only simplifying the complicated structure shown in FIGS. 11, 12 but also improving the reliability.

FIG. 14 shows an eighth embodiment of the present invention. According to this embodiment of the invention, the antenna module 9 is mounted on a dome-shaped quartz bell-jar 21. The reason for the use of the dome-shaped bell-jar is that the thickness of such a bell-jar can be reduced in view of the inherent structural strength thereof. The adoption of such a thin-walled bell-jar results in improved ignitability of the plasma inasmuch as the coupling of the plasma with the antenna module is enhanced.

According to the ninth embodiment shown in FIG. 15, two antenna modules 9 are arranged in the form of concentric circles and are respectively connected to high-frequency sources of different systems. The levels of currents flowing into antennas 92, 96 and the relative phases are controlled by the high-frequency sources 191, 192 for driving the respective antennas, whereby the distribution of the quantity of ions reaching a specimen can be regulated since the position where the plasma is generated is controllable.

According to a tenth embodiment, as shown in FIG. 16, a quartz bell-jar 21 in the shape of a hat is provided and the antenna module is installed on the side of the bell-jar. By forming the bell-jar into a hat shape, the wall thickness of at least the side portion of the bell-jar can be reduced with the effect of improving the coupling with the plasma.

As set forth above, according to the present invention, it is possible to provide a method and apparatus capable of meeting various requirements (plasma uniformity, uniformity controllability, the provision of opposed grounding electrodes and so on) of the plasma processing chamber, which is simple in construction.

According to the present invention, further,

(1) abnormal discharge and sputtering resulting from the electrostatic coupling of the plasma with the antenna are obviated, which contributes to decreasing the amount of foreign matter and improving long-term reliability;

(2) ignitability and stability of discharge are improvable since the antenna can be placed closer to the plasma;

(3) abnormal discharge coupling originating from high antenna voltage can be obviated with increased stability as well by easily ensuring matching since the antenna impedance can be lowered; and

(4) a grounding electrode can be formed in parallel to the specimen since a conductor is placeable even in the space surrounded by the antenna module, so that processing uniformity is improved.

What is claimed is:

1. A plasma processing method of processing a specimen by a plasma generated utilizing a microwave introduced from an outer periphery of an upper face of a process chamber, the process chamber having a gas supplied thereto and the specimen being held in the process chamber, the method comprising the steps of independently controlling a density distribution of the plasma in the process chamber by position adjustment of an electron cyclotron resonance layer or a magnetic field gradient.

2. An electromagnetically coupled plasma processing method of processing a specimen by a plasma utilizing an electromagnetically coupled plasma processing apparatus including a process chamber, a specimen holder which holds the specimen in the process chamber, a gas introducer which introduces gas into the process chamber, and a plasma generator, the method comprising the steps of arrangement at least two antenna modules in concentric circles, each of the antenna modules including a loop antenna for carrying a high frequency wave, arranging a cavity resonator to surround the loop antenna so as to form the plasma generator, wherein and generating the plasma by utilizing the loop antenna carrying the high-frequency wave so that a density of the plasma is independently controlled.

3. A plasma processing apparatus comprising a process chamber, a specimen holder which holds the specimen in the process chamber, a gas introducer which introduces gas into the process chamber, and a plasma generator including a microwave source which enables generation of the plasma by introducing a microwave from an outer periphery of an upper face of the process chamber, wherein a density distribution of the plasma in the process chamber is independently controlled by position adjustment of an electron cyclotron resonance layer or a magnetic field gradient.

4. An electromagnetically coupled plasma processing apparatus comprising a process chamber, a specimen holder which holds a specimen in the process chamber, a gas introducer which introduces gas into the process chamber, and a plasma generator, the plasma generator including at least two antenna modules arranged in concentric circles, each of the antenna modules including a loop antenna for carrying a high frequency wave, and a cavity resonator arranged so as to surround the loop antenna so that a density distribution of the plasma is independently controlled.

* * * * *